Update on LIGO and gravitational-wave Astrophysics

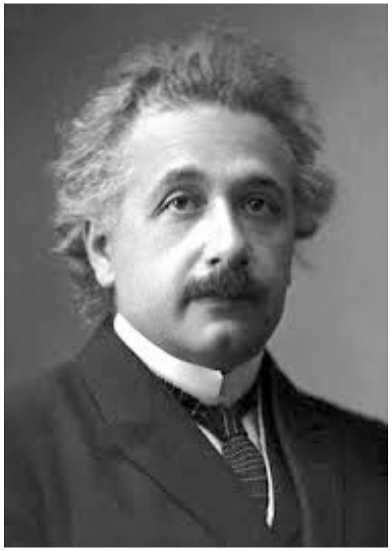
LIGO

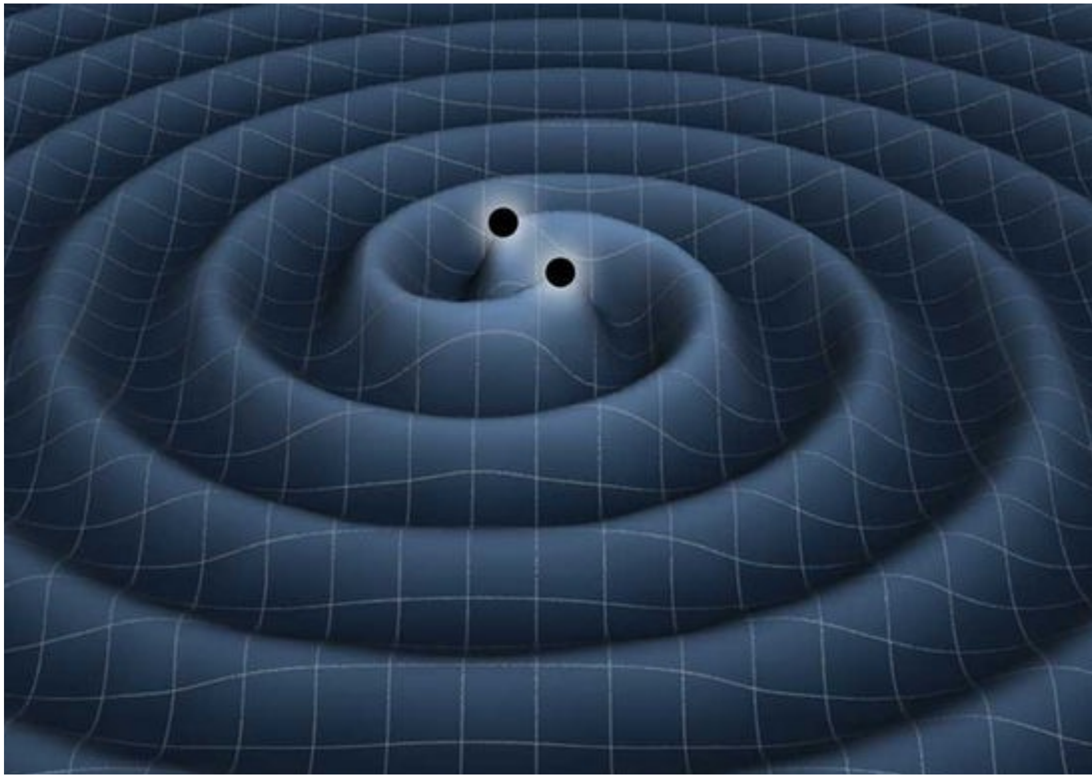
Gravitational Waves (GWs)

- The waves of the electromagnetic force are realized as (electric and magnetic) fields which propagate through space and time. [Maxwell, 1865]

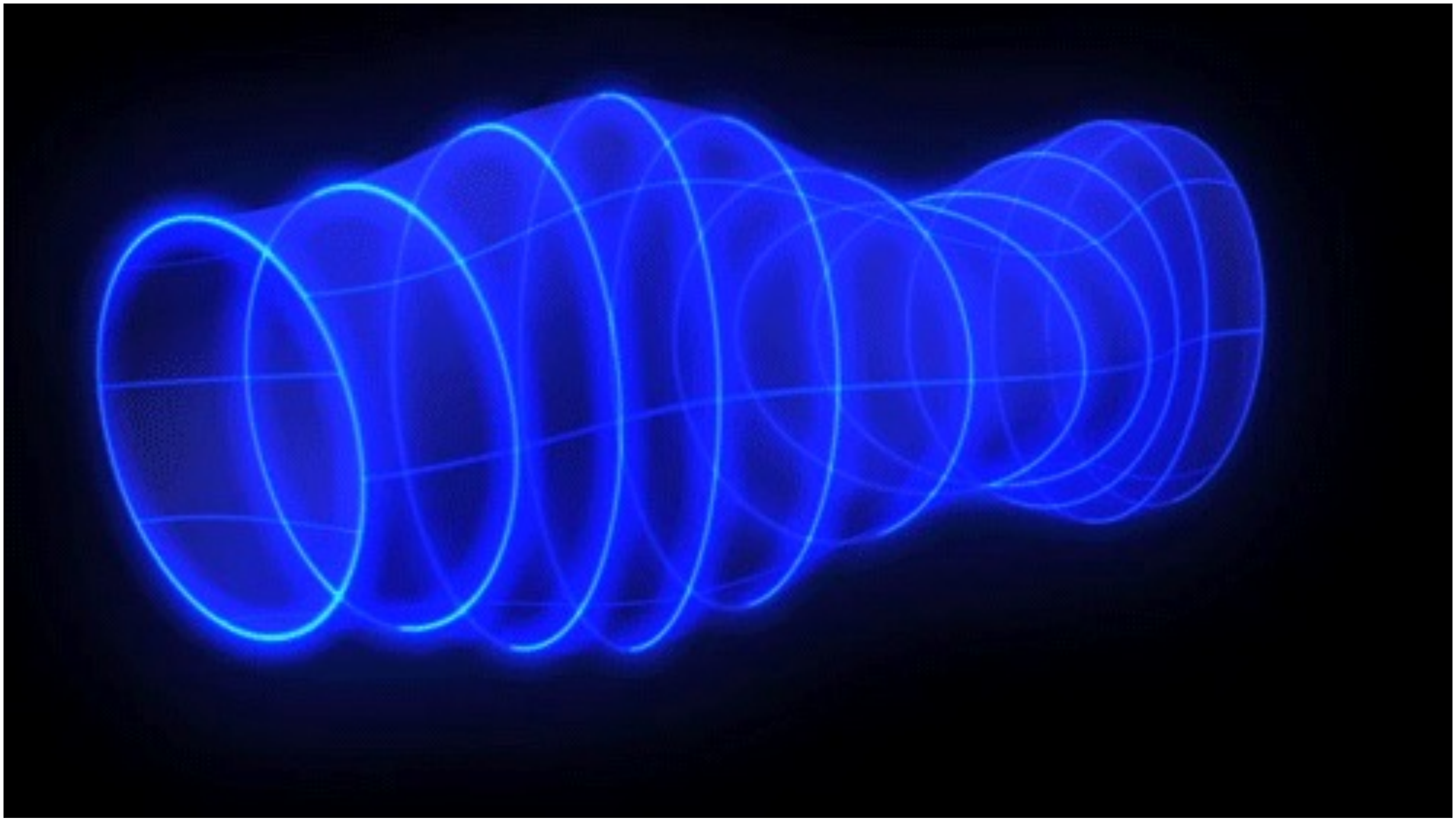
- General Relativity describes gravity in terms of a spacetime which is deformable. [Einstein, 1915]
- GWs are oscillations of that spacetime. [Einstein, 1916]

- “ripples in spacetime”



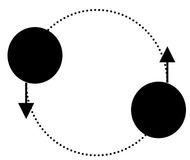


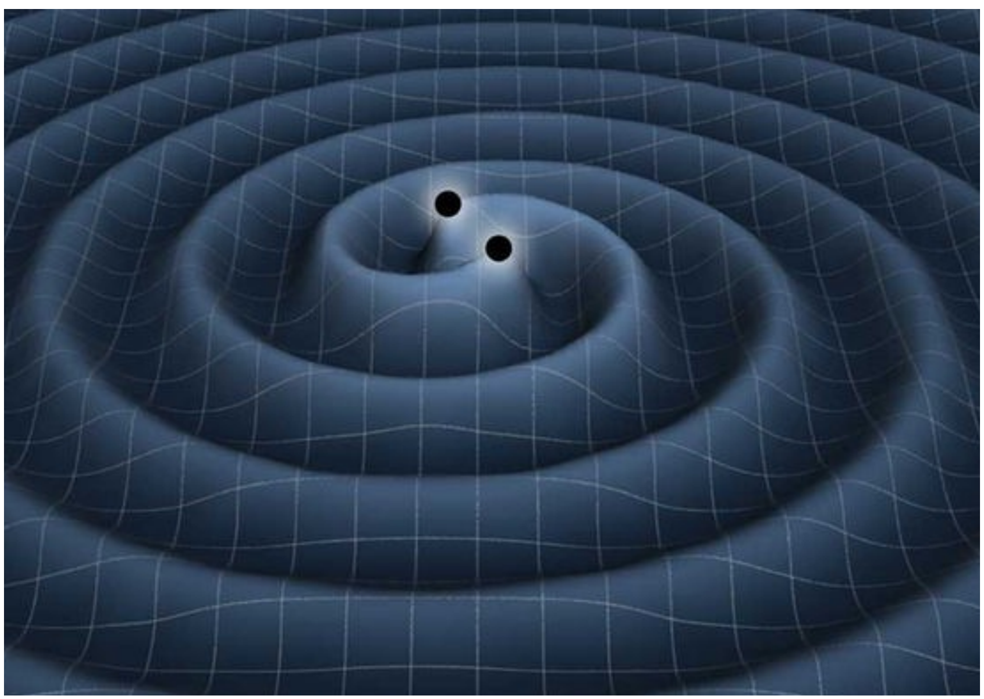
Propagating gravitational wave



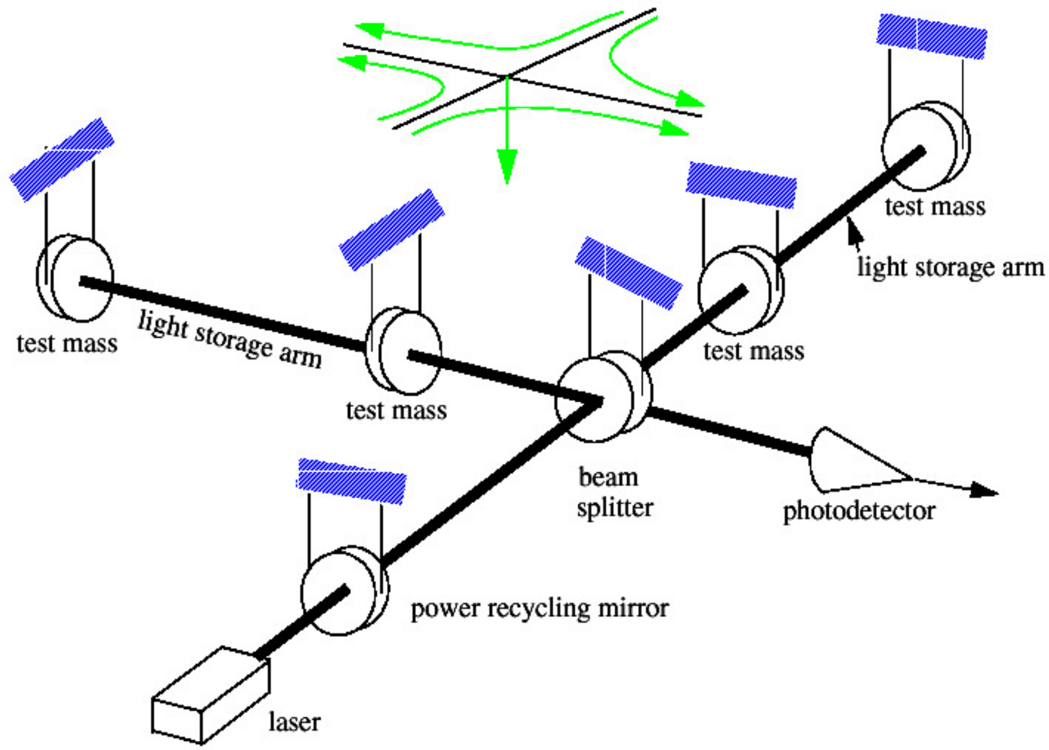
Gravitational waves and LIGO: short version

Binary black hole system





As detected by LIGO:

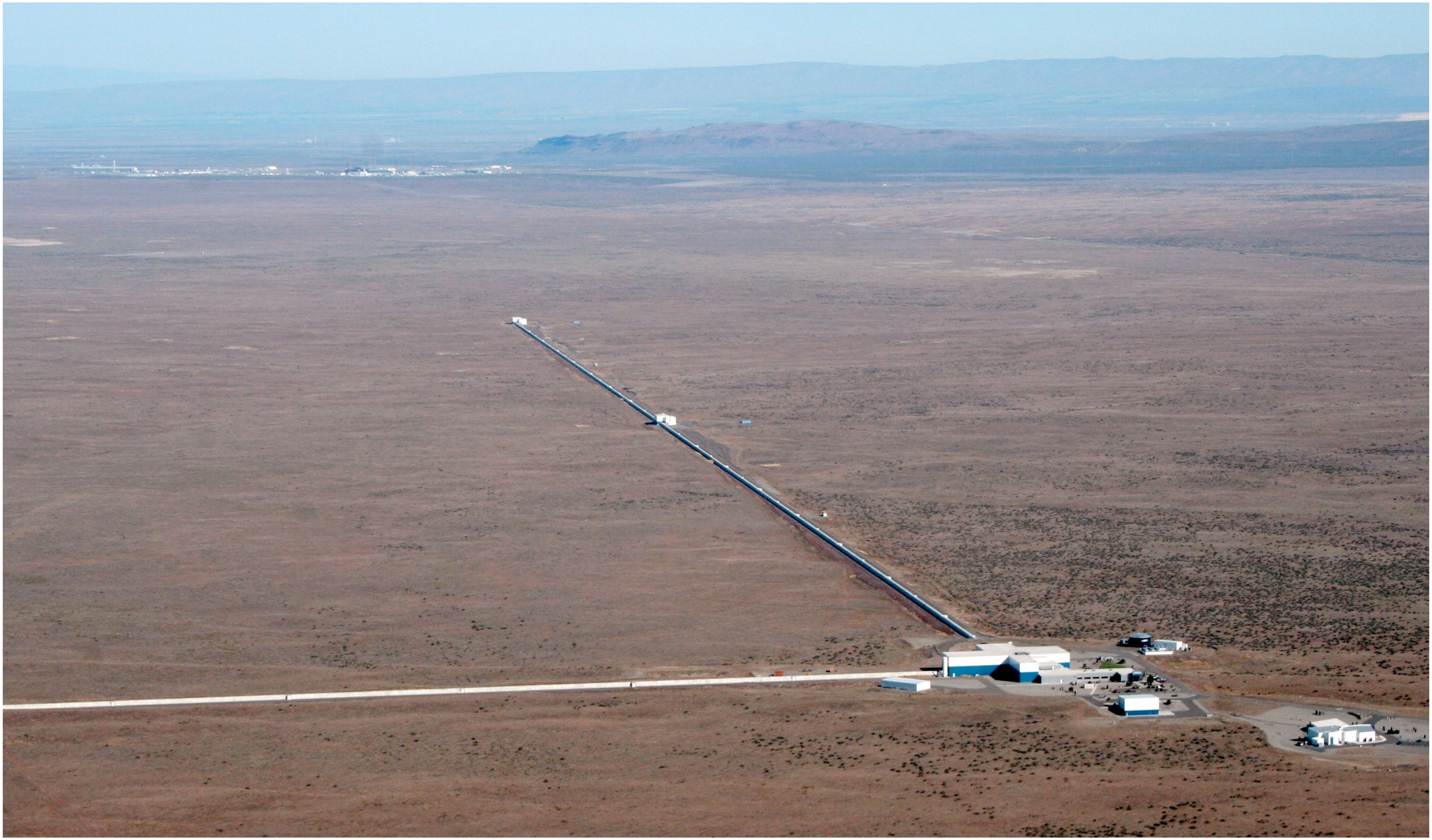


GW ripples manifest as a space strain h, where $h = \Delta L / L$

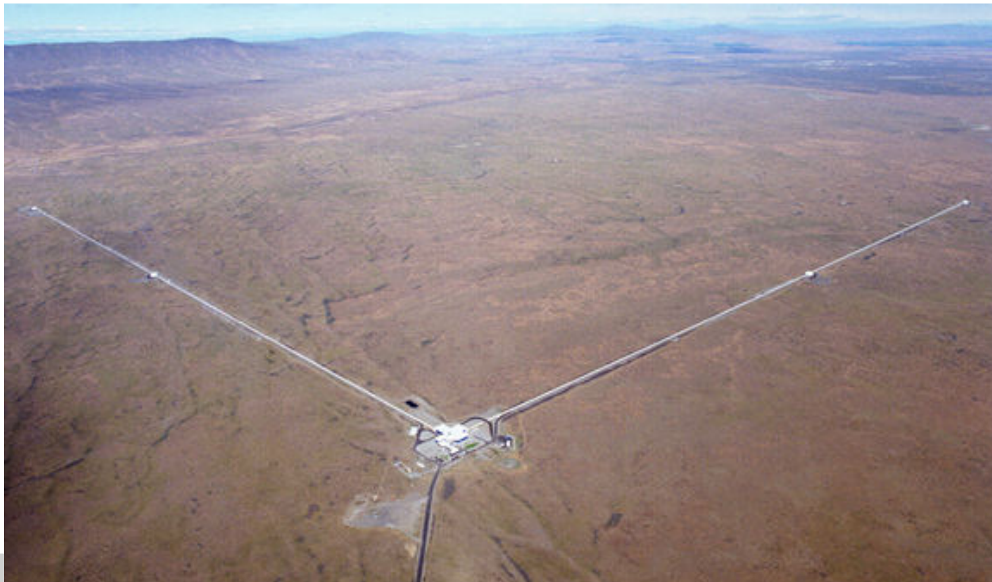
Realistic sources: $h \sim 10^{-23}$

$\Rightarrow \Delta L \sim 10^{-19}$ m (Yikes !)

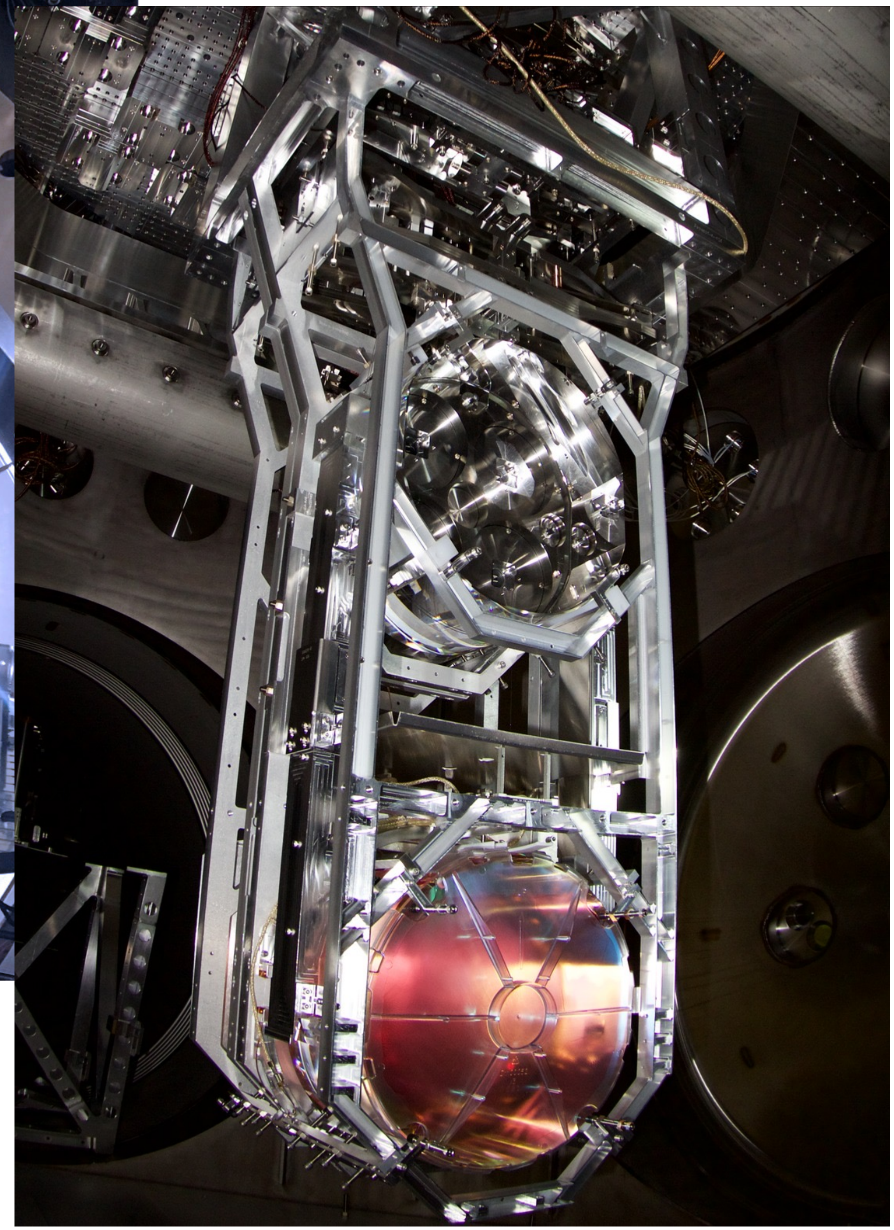
LIGO Hanford Observatory



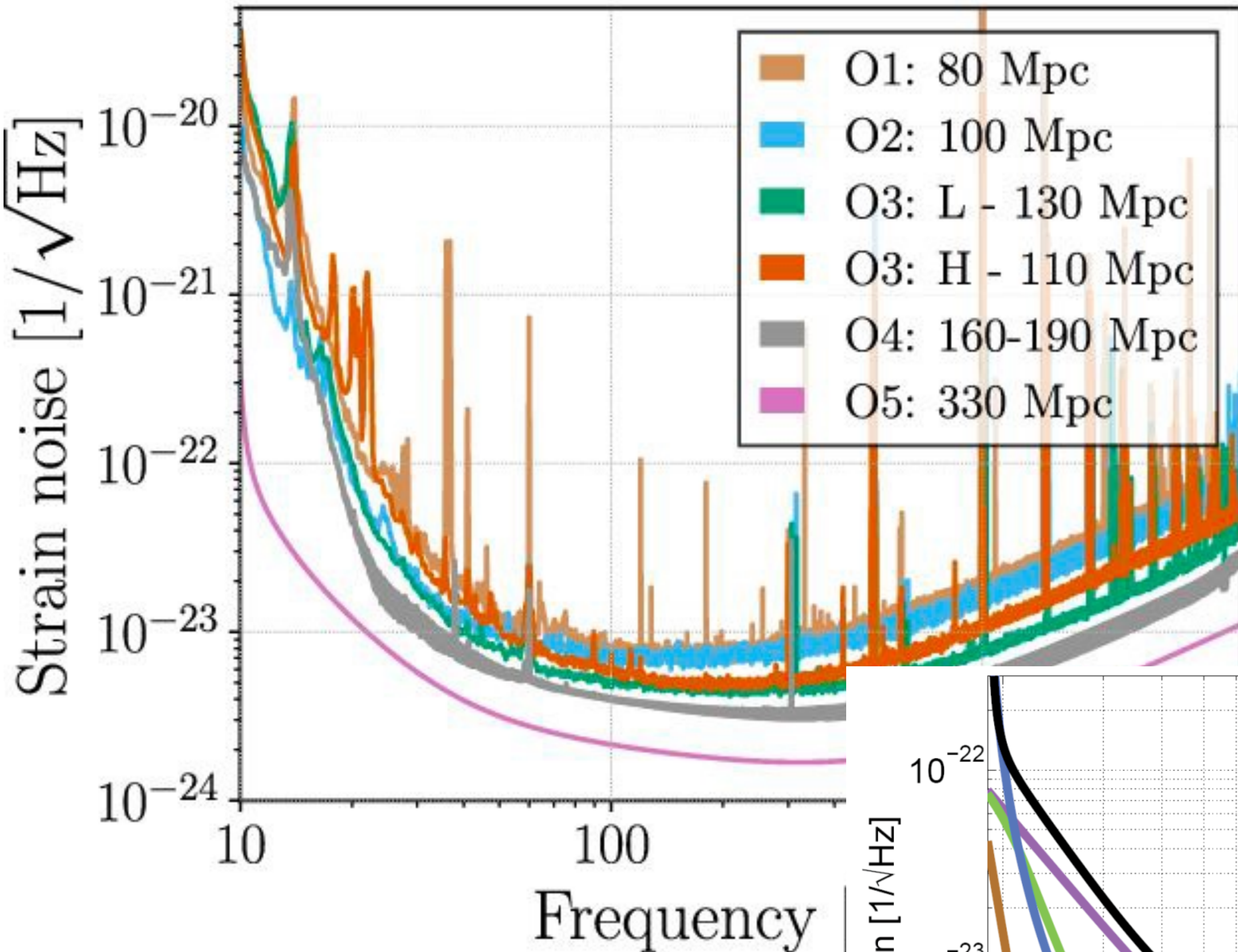
observatories

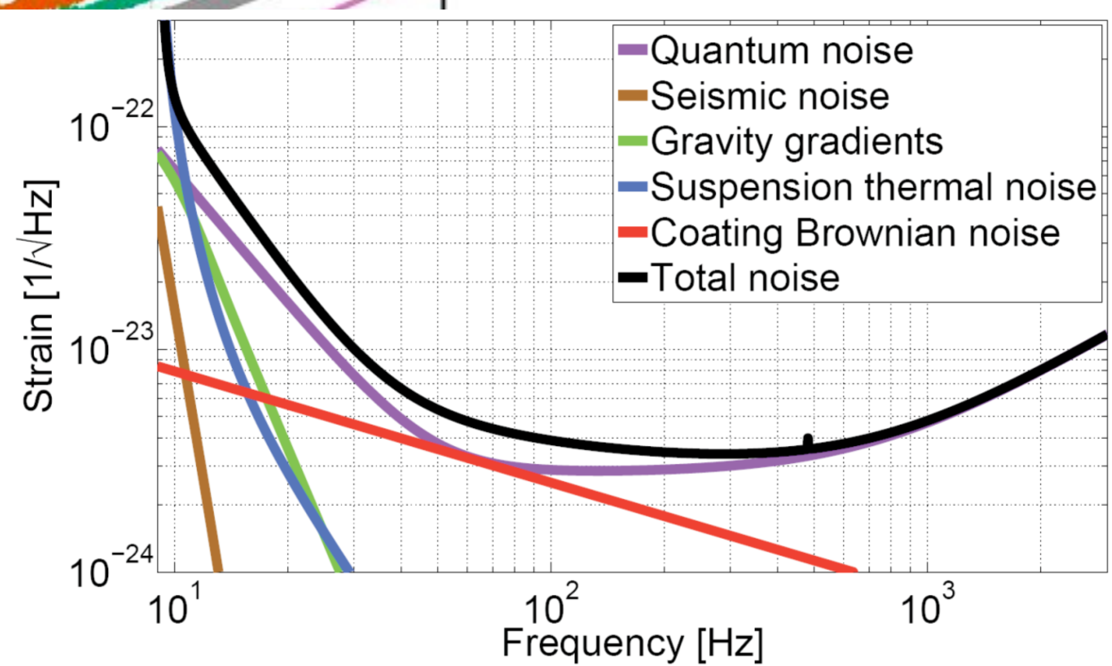


Inside the vacuum chambers

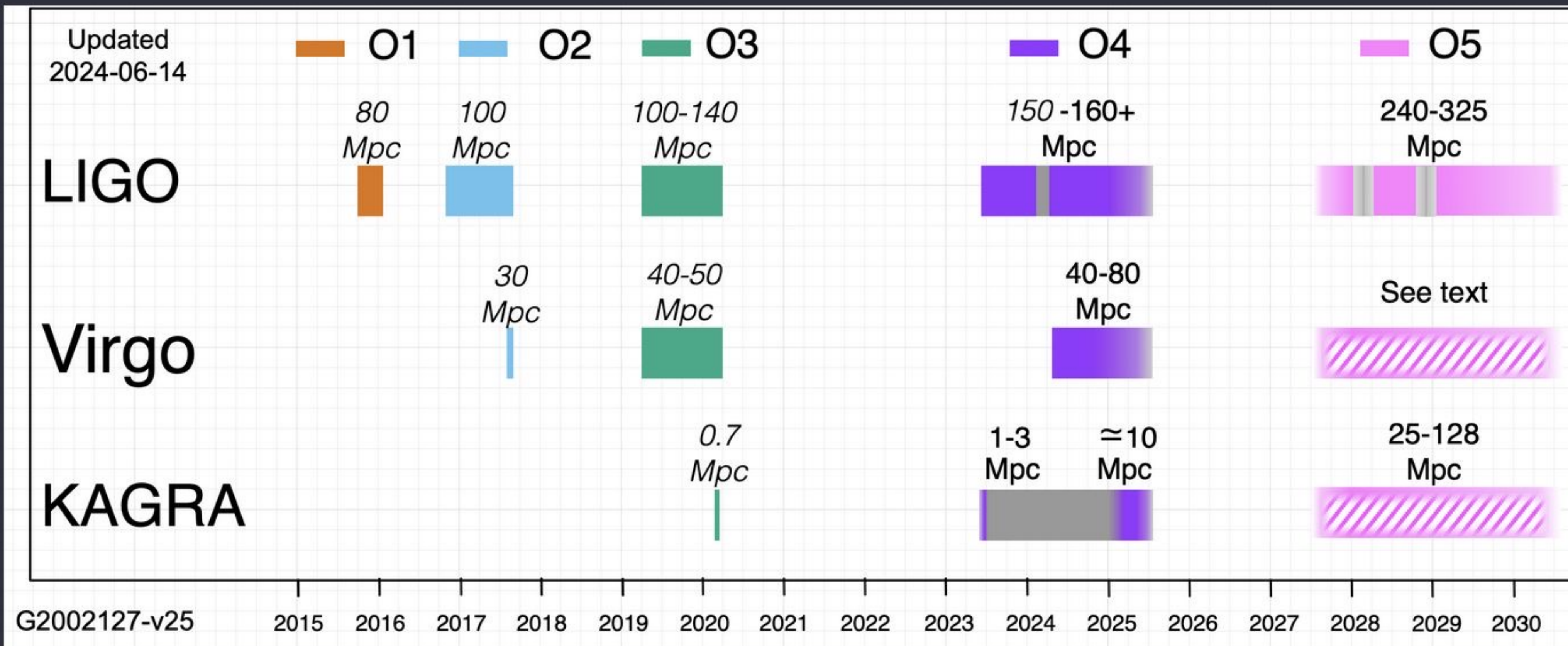


Reducing the noise → increasing sensitivity



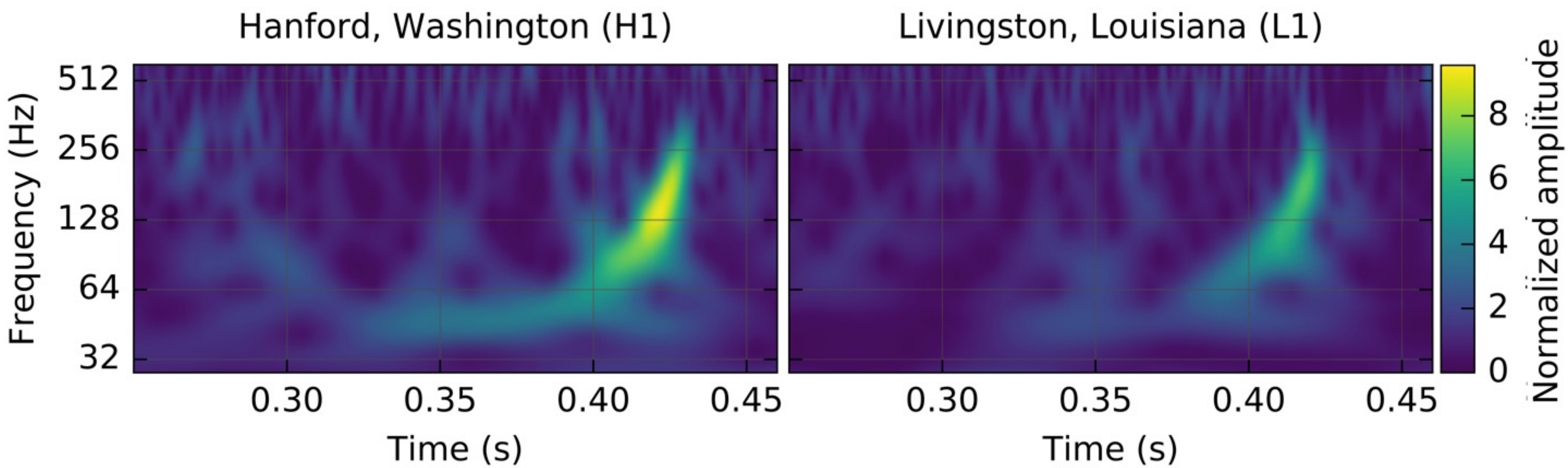


Observing runs



The O5 start dates, duration, and sensitivities are current best guesses, and will likely be adjusted as we approach that run for all the detectors (see text).

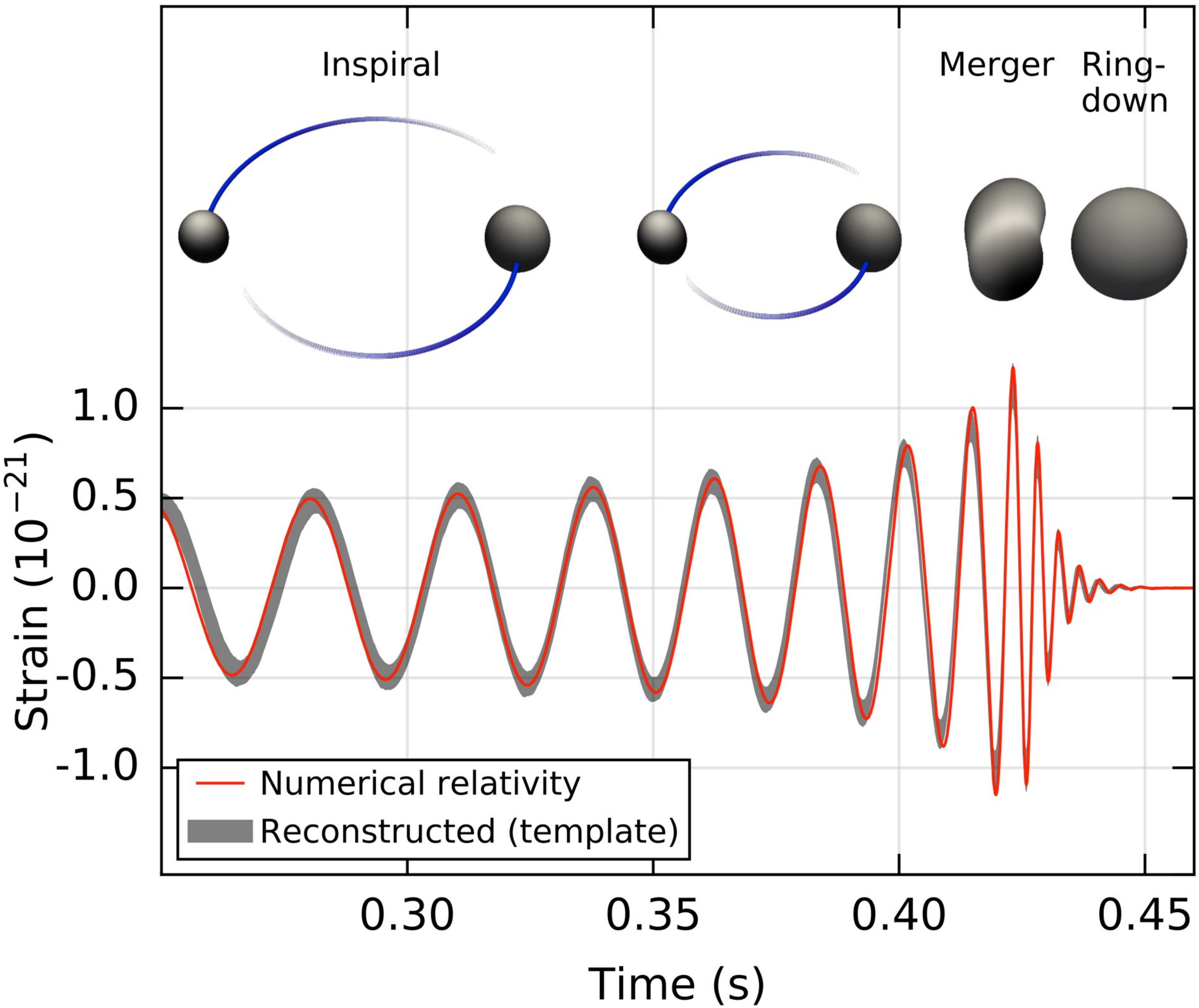
Boom !



GW150914

- First observation of GWs
- First direct observation of black holes

Binary black hole inspiral, merger, ringdown

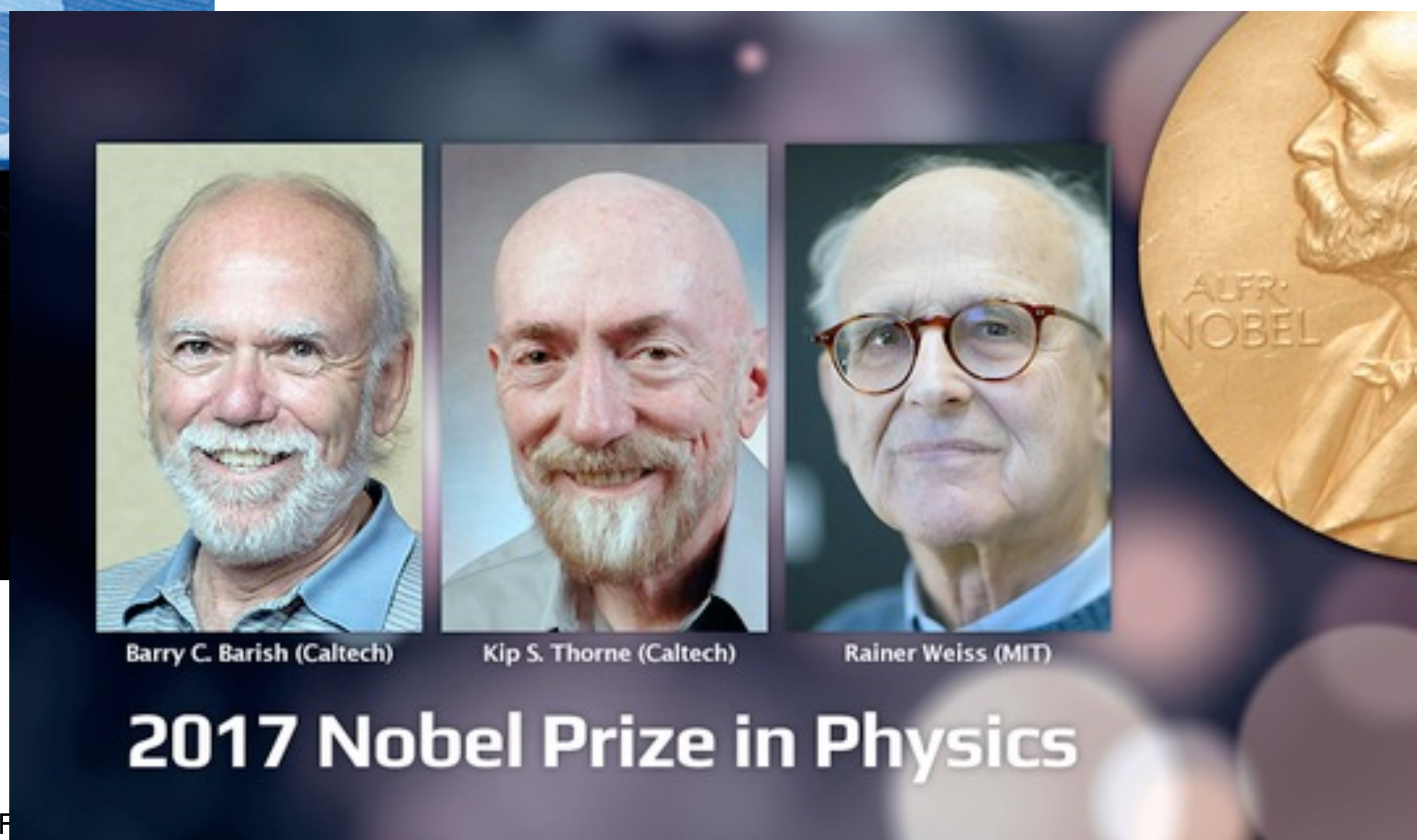


LIGO

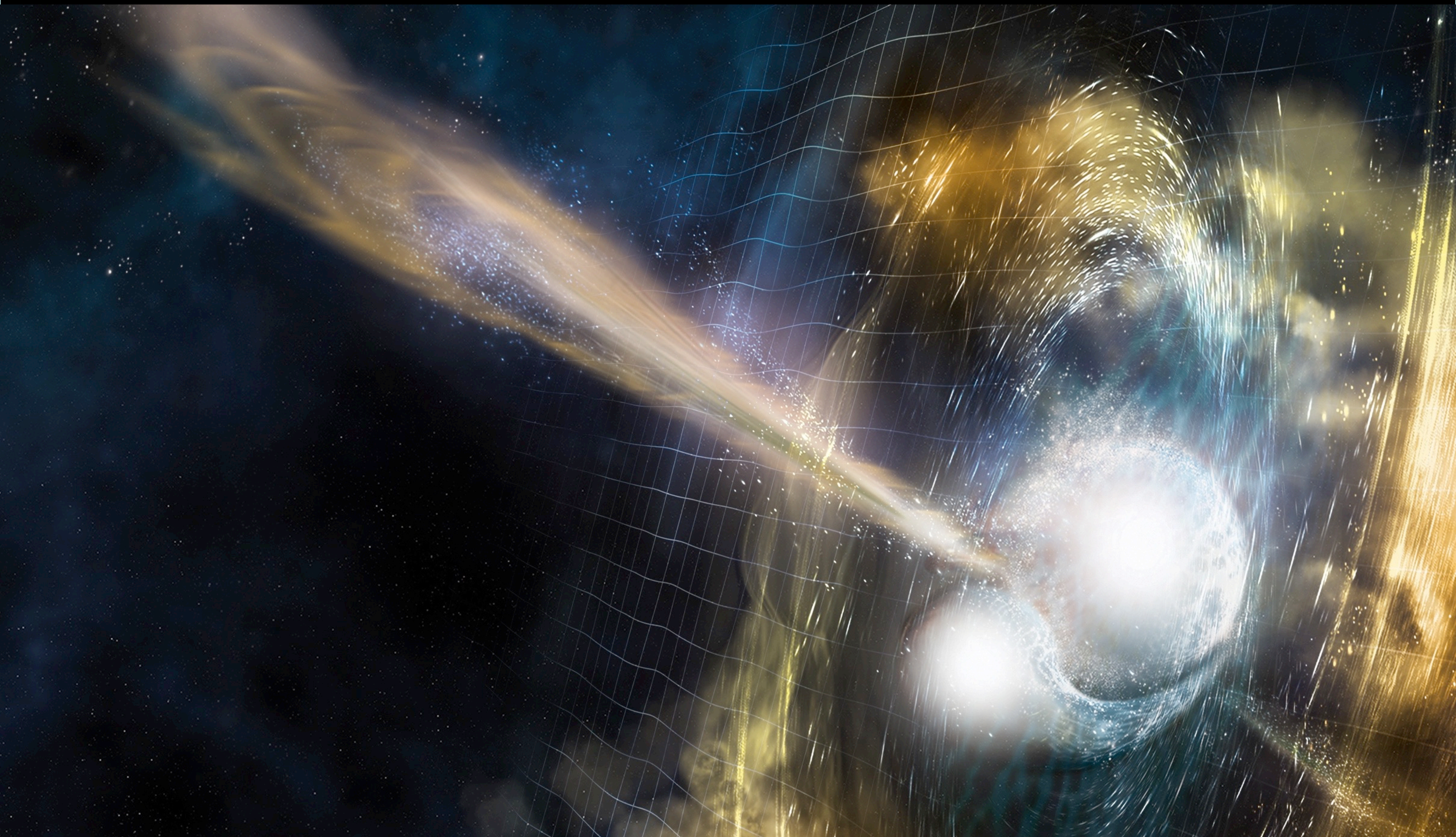
Simulated Nearby View – slowed down 100X

Video link: https://youtu.be/I_88S8DWbcU

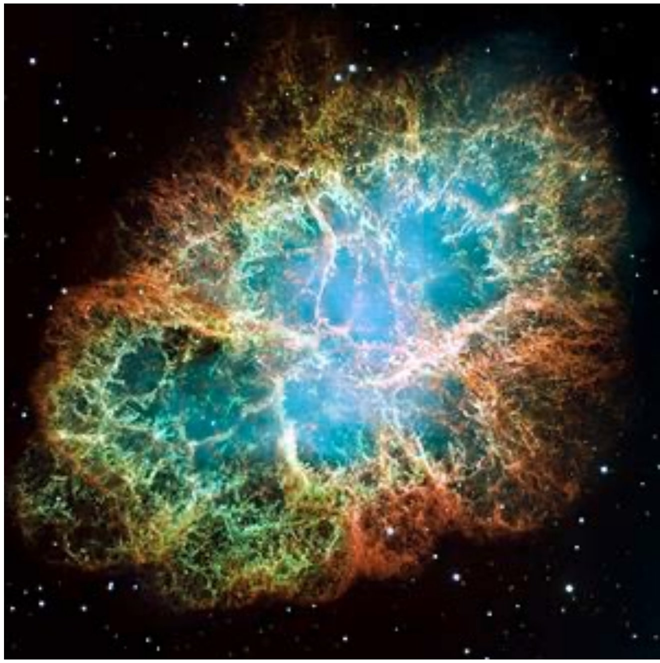
GW Discovery Accolades



Boom II:
Binary neutron-star merger August 17, 2017 (O2)

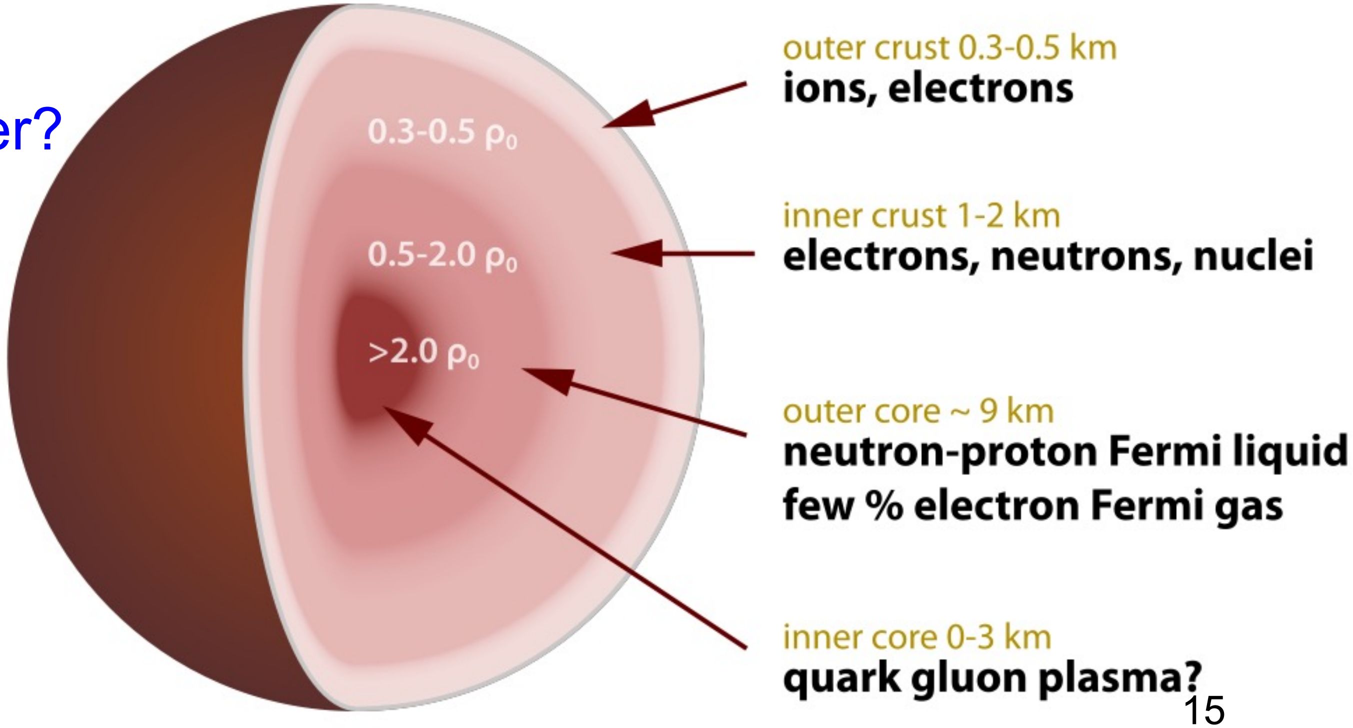


Neutron stars

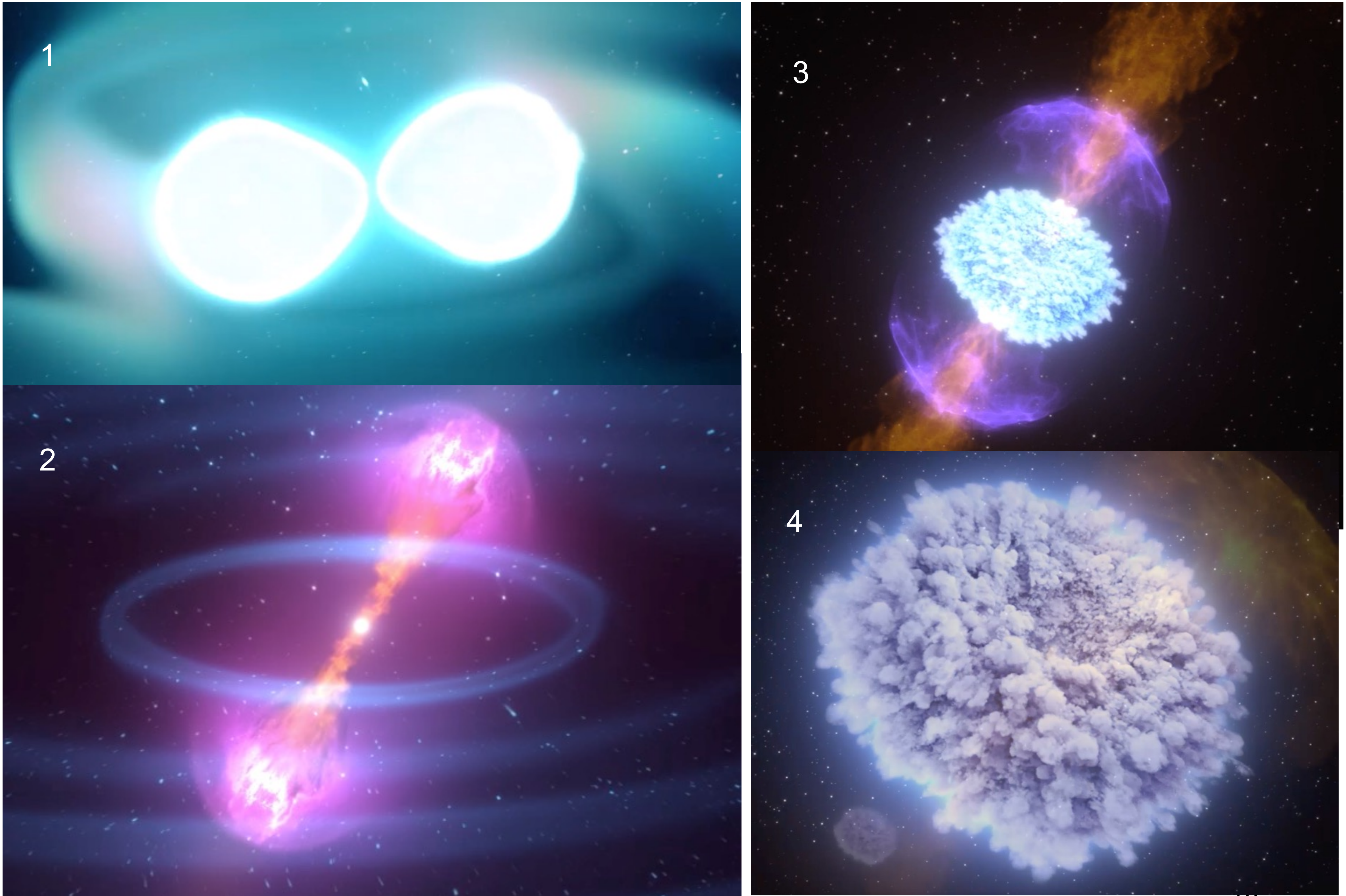


- NS result from normal stellar evolution for massive stars in the range 8 to 40 $M_{\odot}$
  - Fusion to Iron
  - Supernova (Type II)
- NS mass: 1 to 3 $M_{\odot}$
  - (heavier remnant → black hole)
- Radius ~ 10 km

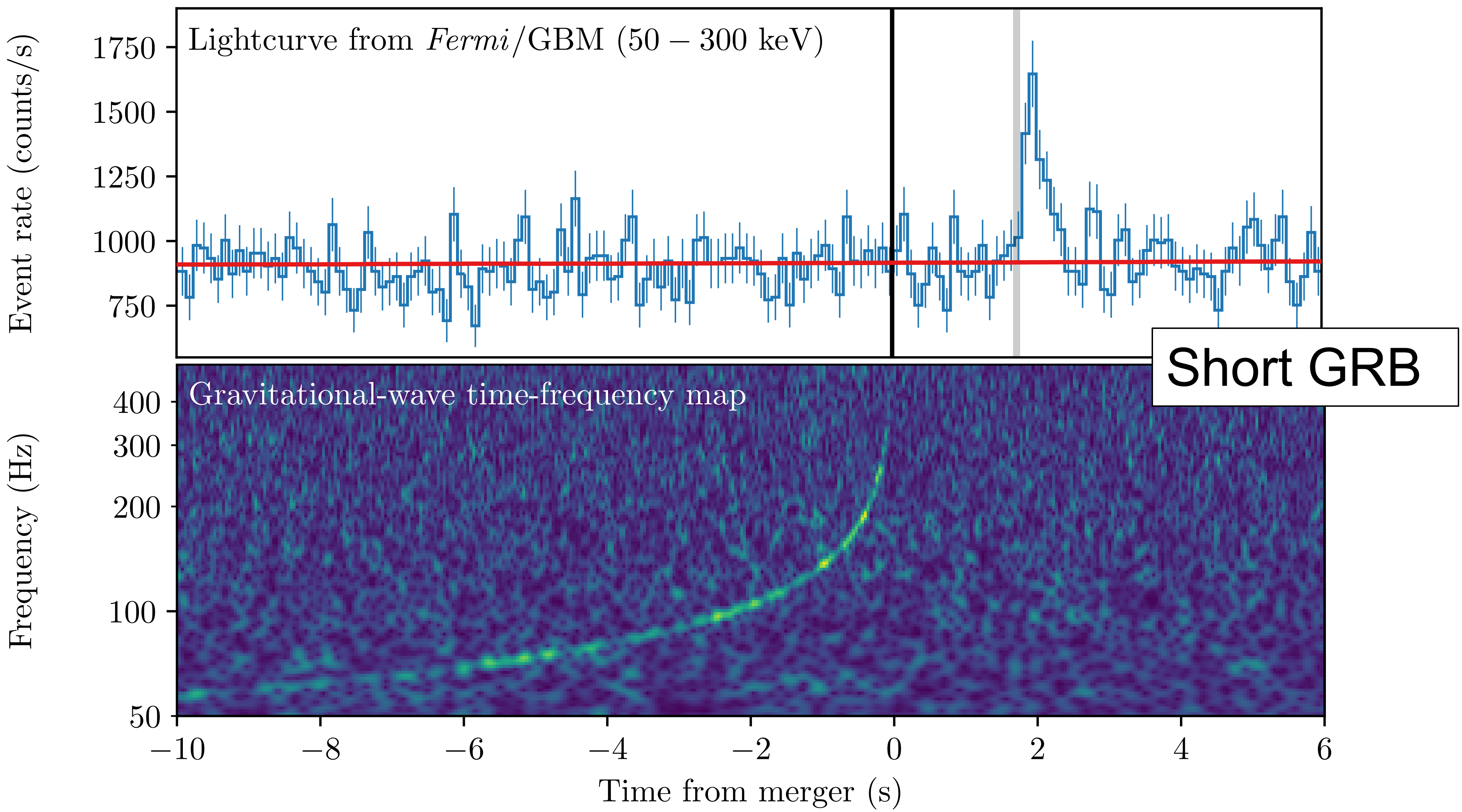
  ~ nuclear density! At surface: g=$2\times10^{12}\ m/s^2$
- Mysterious composition
  - new phases of matter?
  - quark matter?
  - dark matter?



NS Merger, gamma-ray burst, afterglow (“kilonova”)



August 17, 2017: LIGO+Fermi



$\Delta t = 1.74 \pm 0.05$ s

Speed of gravity

$$\Delta t = 1.74 \pm 0.05\,\mathrm{s} = \Delta t_{\mathrm{astro}} + \frac{D}{c^2}(c_g - c)$$

- Δt_astro ~2 s is very reasonable
  - Our prior based on astrophysics of SGRBs was Δt = [0,4] s ✓
  - jet with γ ~ 50 is delayed by ~2 s (relative to v=c) at a photospheric radius of ~30 AU

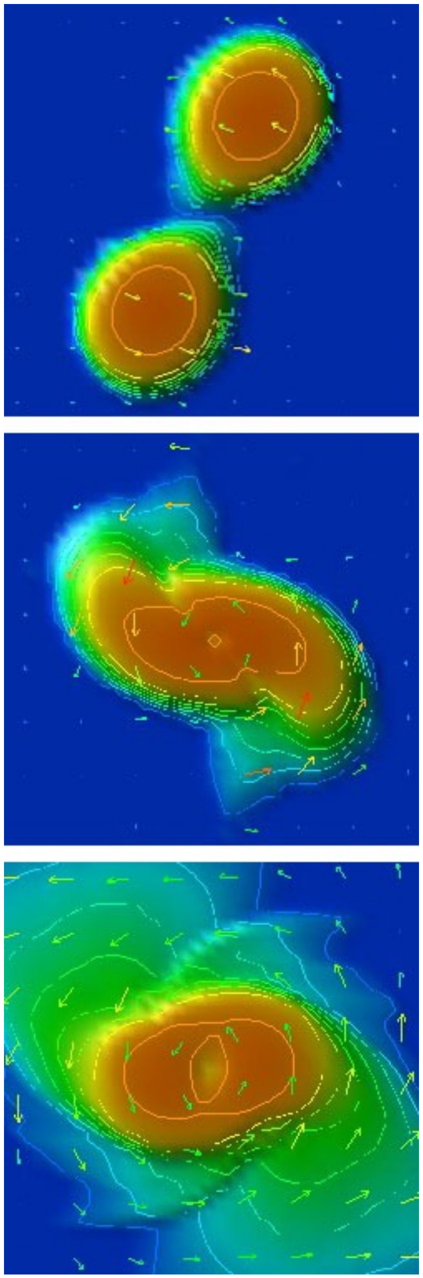
- Limits: (1) Let Δt_astro = 0; (2) Let Δt_astro = 10 s:

$$-3 \times 10^{-15} < \frac{c_g - c}{c} < 7 \times 10^{-16}$$

- Future measurements at different distances can improve this

170817: Astrophysics
The “kilonova”

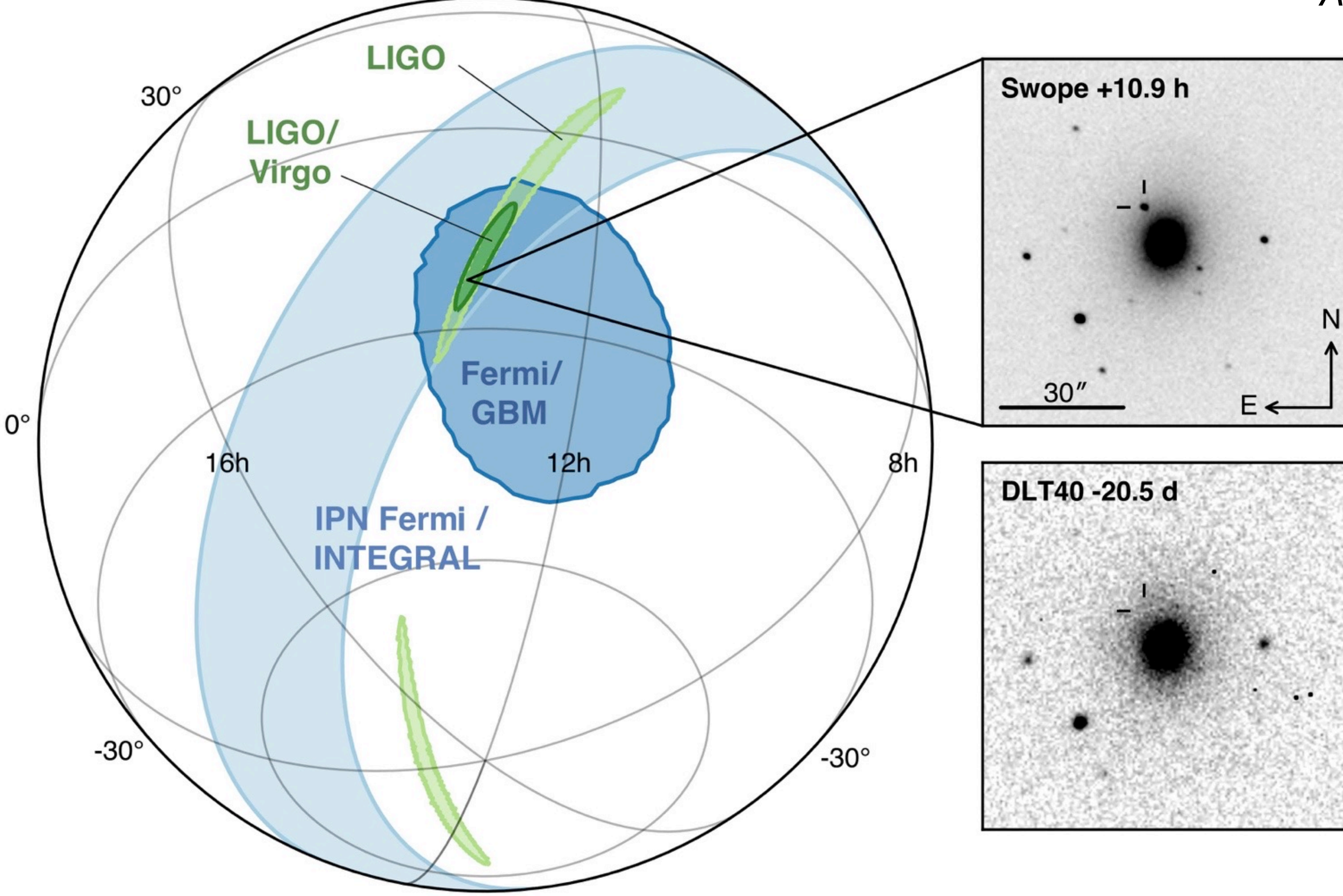
Shibata



- Tidal disruption of the merging neutron stars
  - Disruption depends on NS “stiffness” (EOS)
    - Subtle effects in GW waveforms
- Hypothesis pre-170817:
  - Nuclear ejecta bombarded by neutrons
    - v ~ 0.1-0.3 c
  - Creation of heavy nuclei (r-process)
  - Unstable isotopes → decay → glowing object ”kilonova”
  - Similar to Supernova afterglow

GW localization allows ID of afterglow (kilonova)

ApJL **848** L12



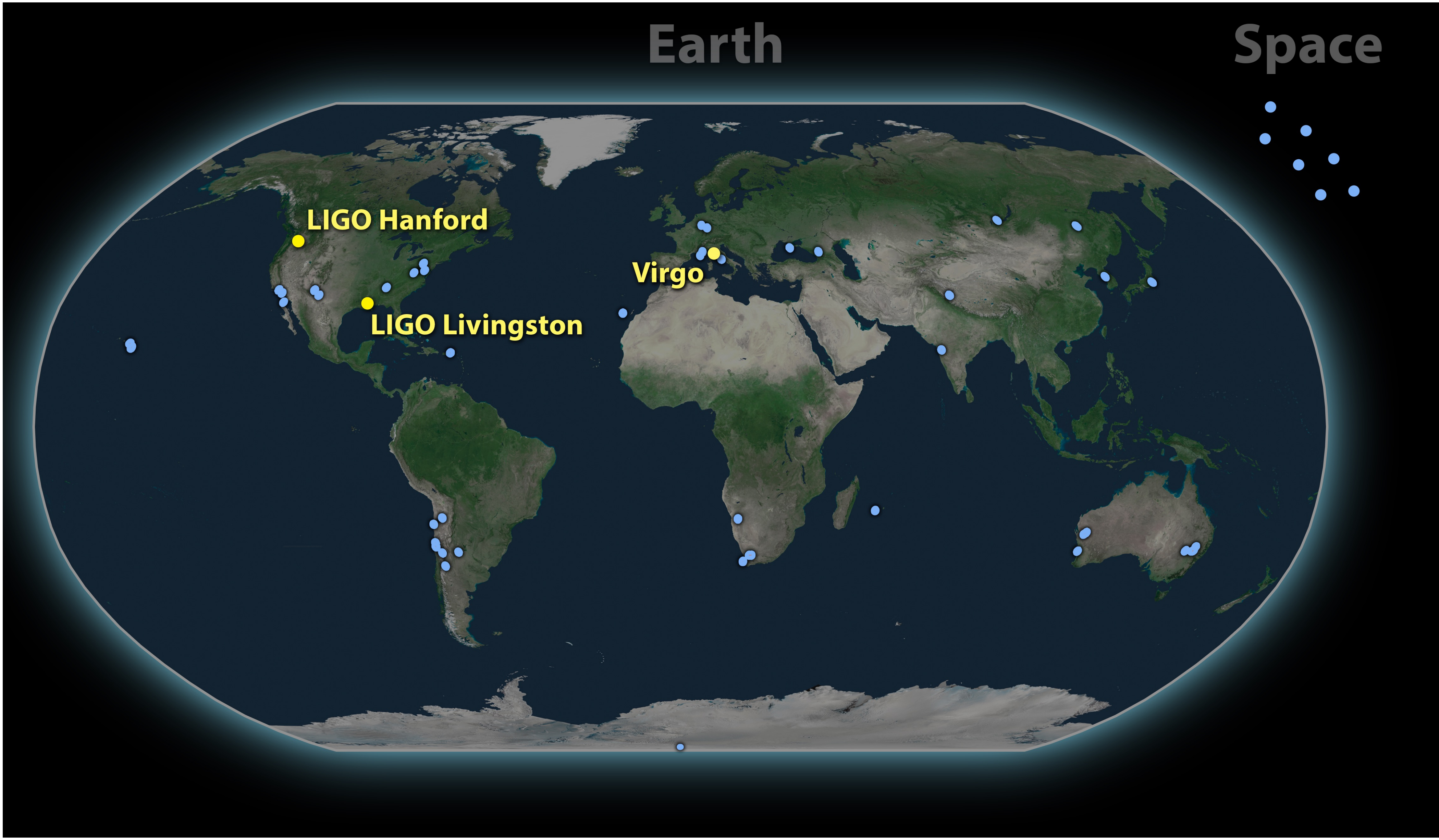
NGC 4993
43 ± 3 Mpc

offset of 2 kpc – typical of kicks

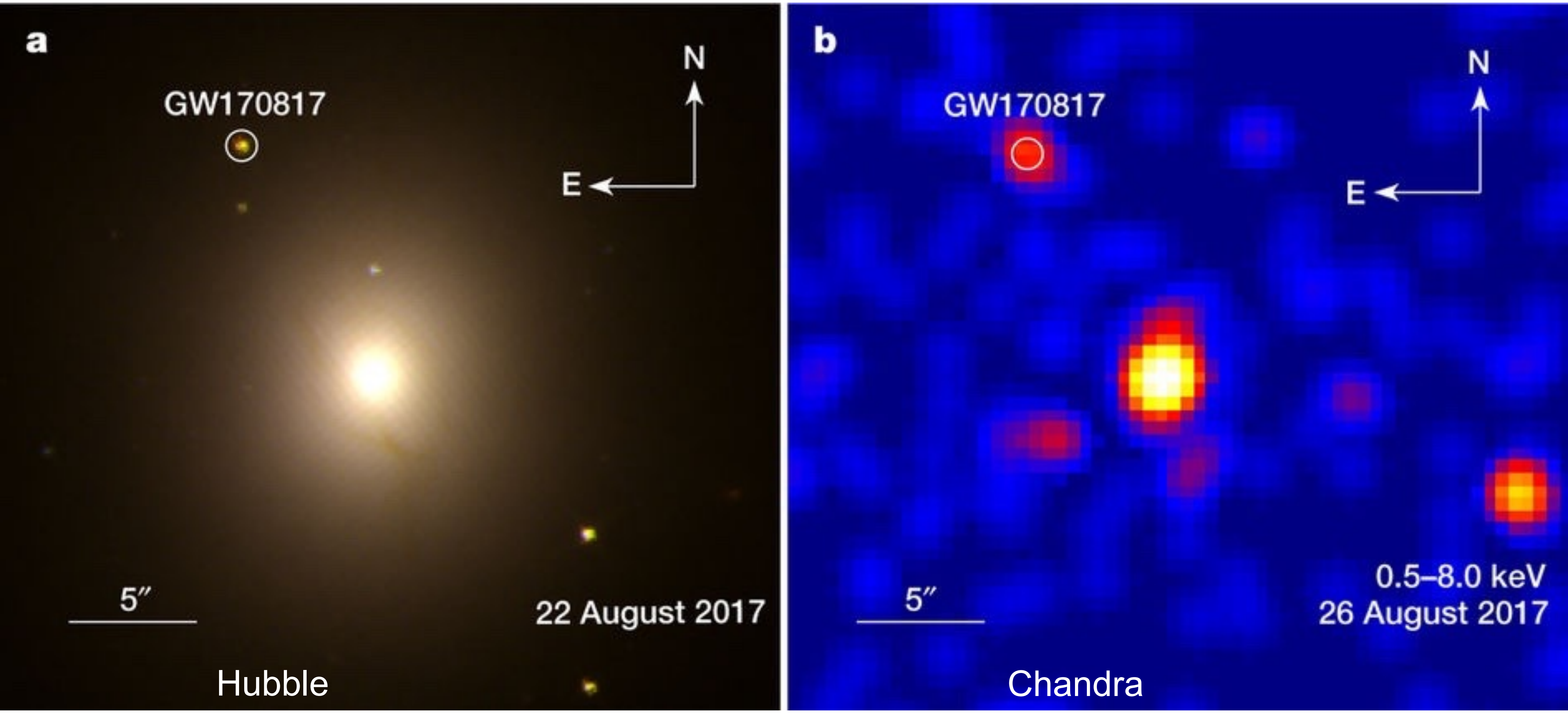
"Multimessenger Astronomy"

LIGO

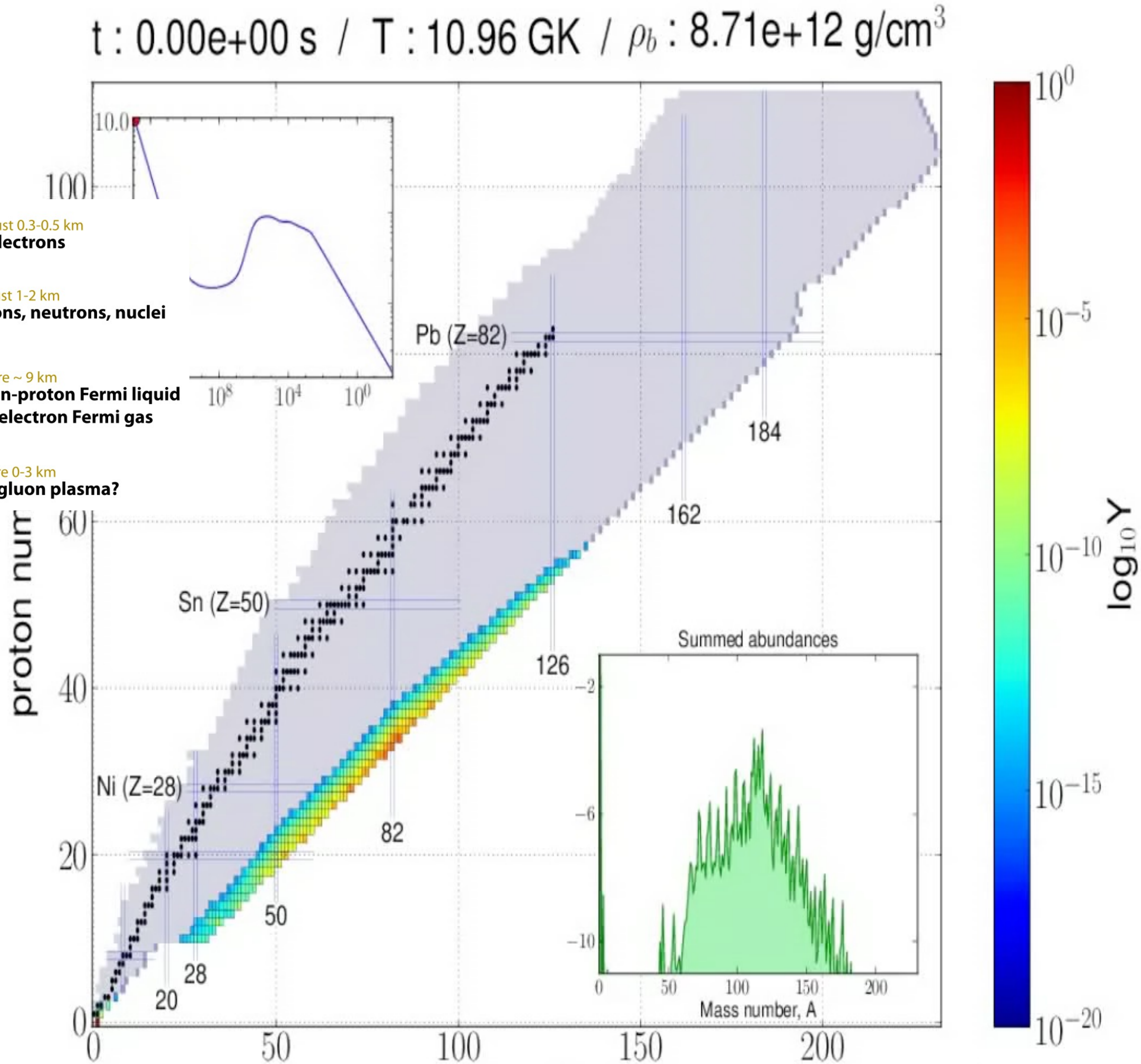
and the astronomy world tuned in

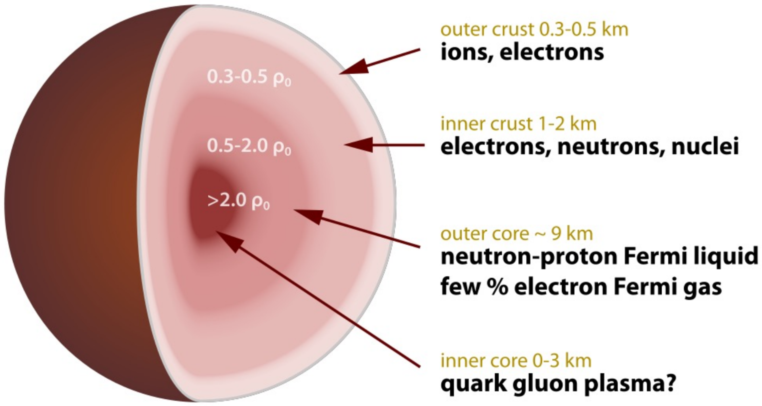


e.g. optical/IR and x-rays



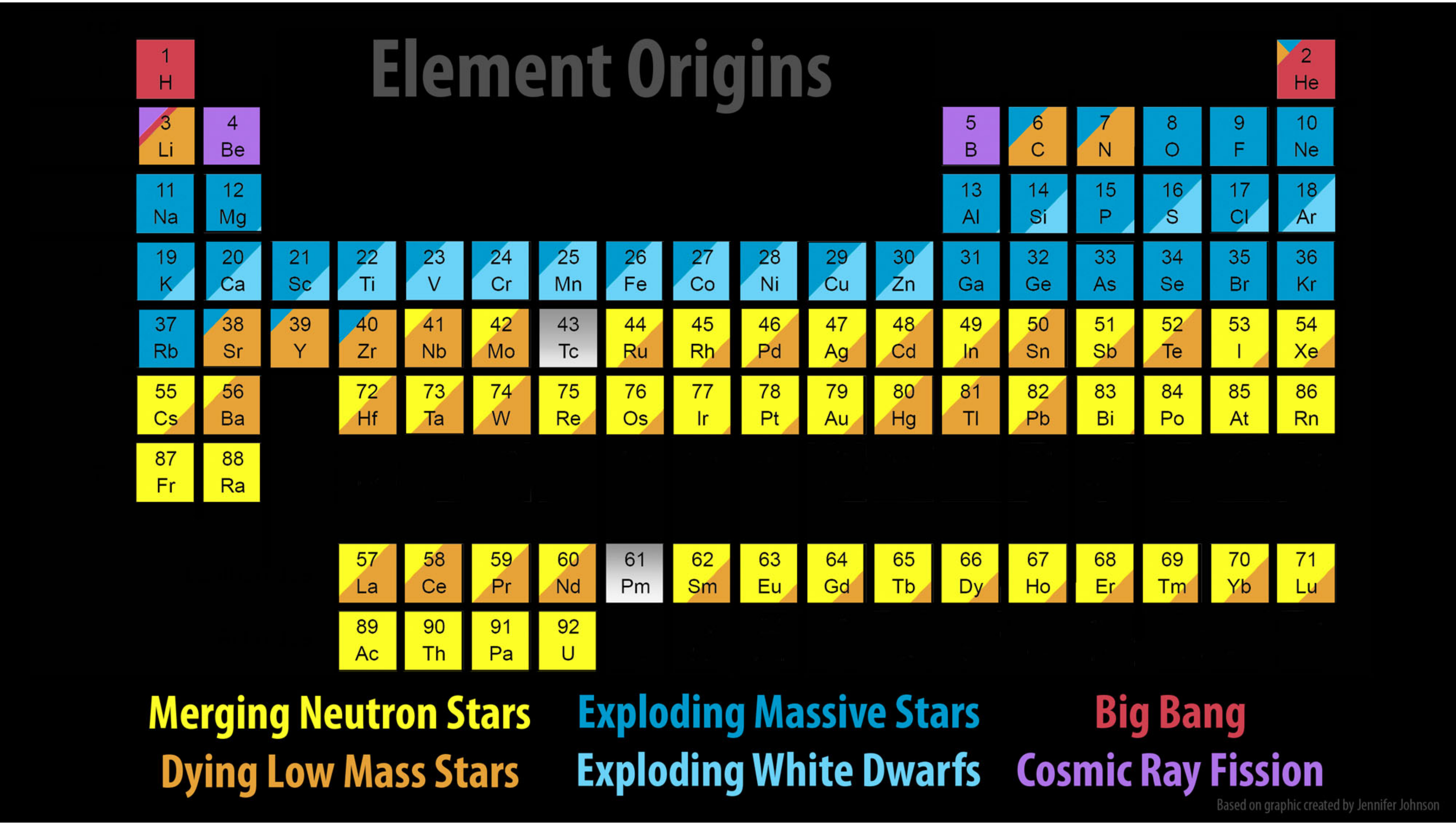
Troja, et al, Nature 2017





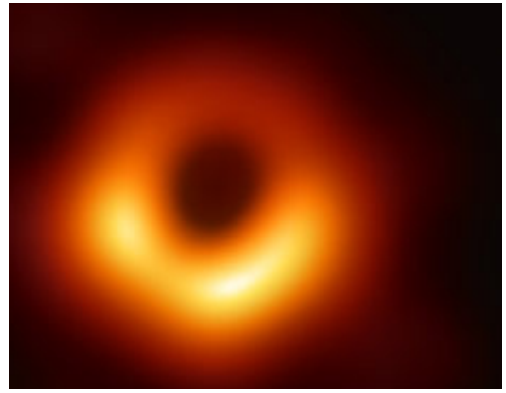
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

Origins of elements: Major Update due to 170817

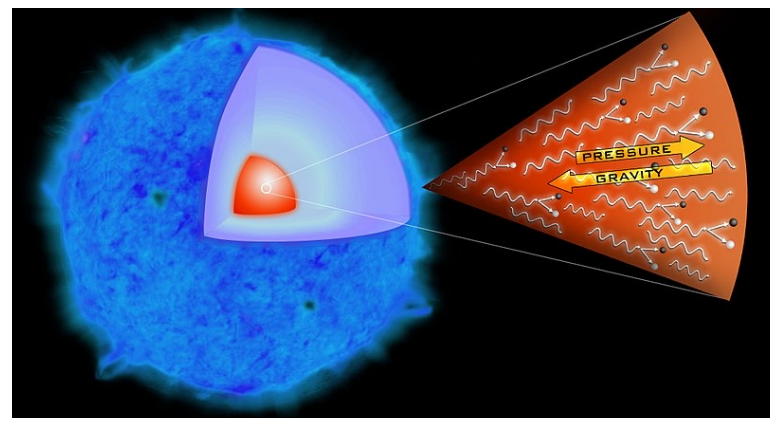


Black hole masses

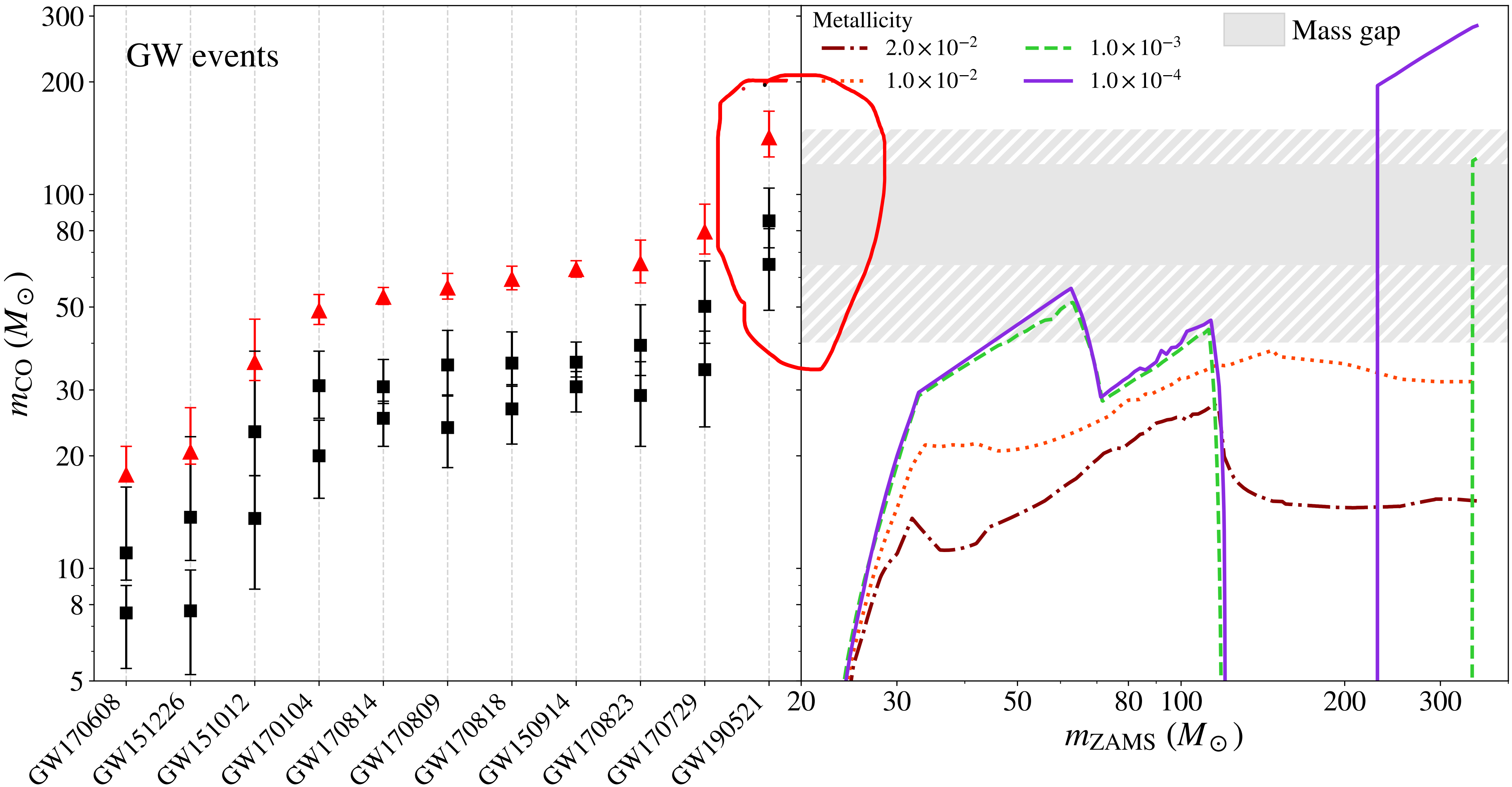
- Supermassive – rapid accretion in early star forming era
  - not observable by LIGO
  - Galactic centers
  - Milky Way: $4 \times 10^6\ M_\odot$
  - M87: $6 \times 10^9\ M_\odot$



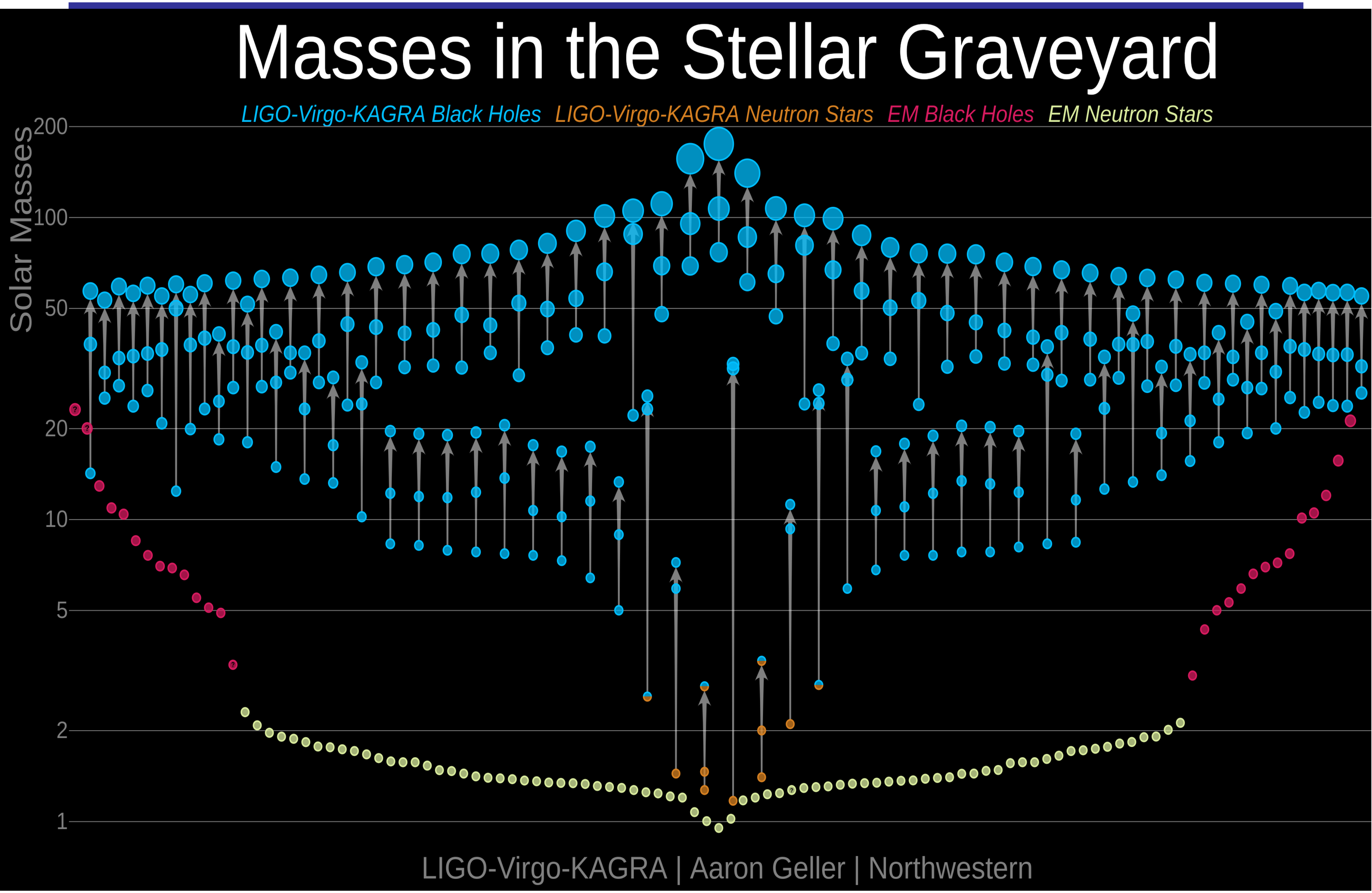
- ‘Stellar mass’
  - Presumed products of stellar evolution
  - $M > 1.4\ M_\odot$
  - If $M < M_\odot$ then primordial (!)
  - $40 < M < 60\ M_\odot$ ‘difficult’ but observed (low metallicity)
  - $60 < M < 130\ M_\odot$ not supposed to exist (pair instability)
  - $M > 130\ M_\odot$ possible; not yet observed



The ‘mass gap’ undone ? Sequential mergers?



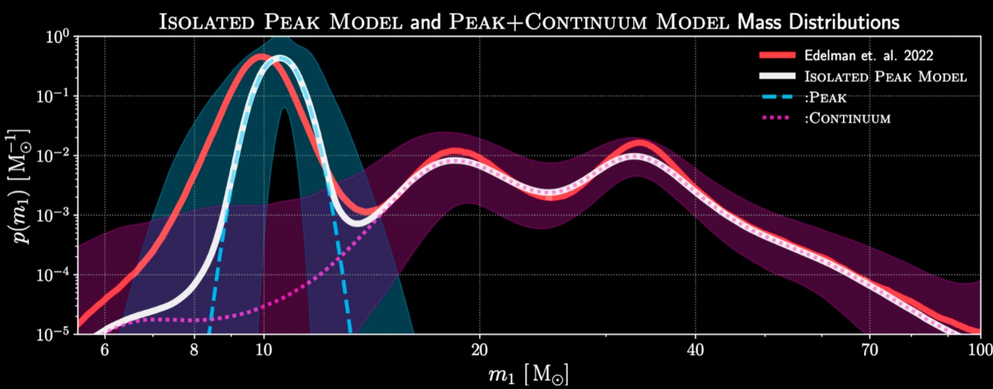
NS/BH mergers detected as of May 2023

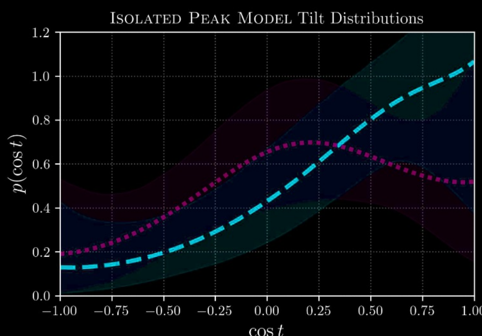


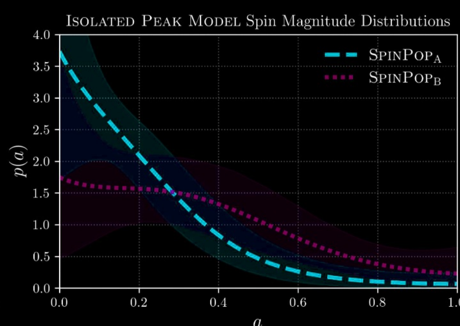
BBH Subpopulation Models

Jaxen Godfrey

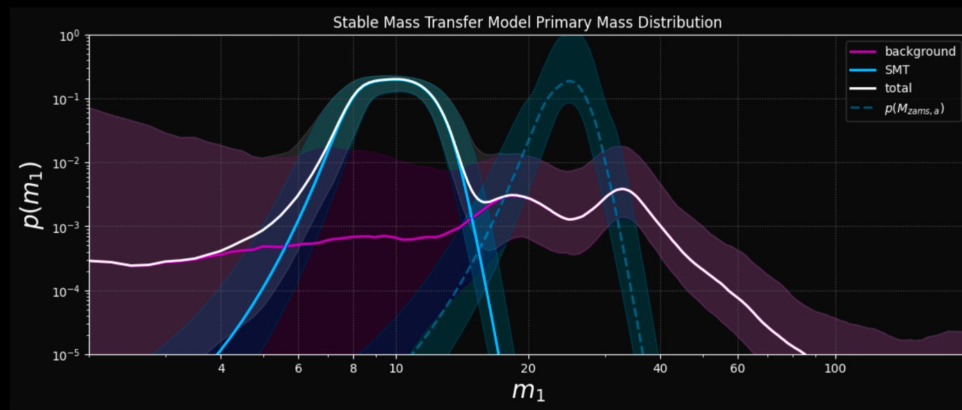
Cosmic Cousins: 10 Msun Subpopulation (update)







New Project: Building a Model for Stable Mass Transfer BHs

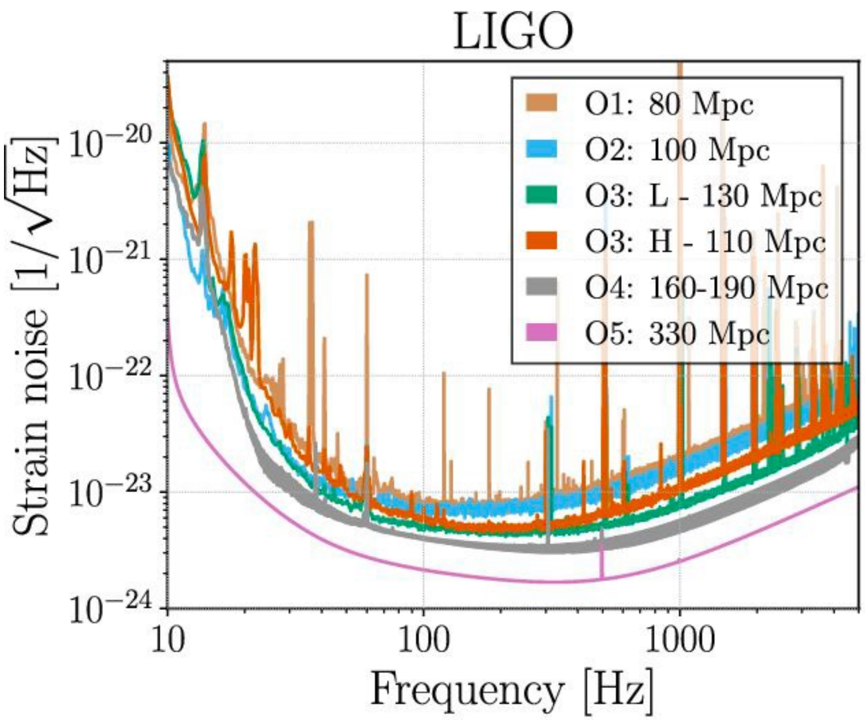


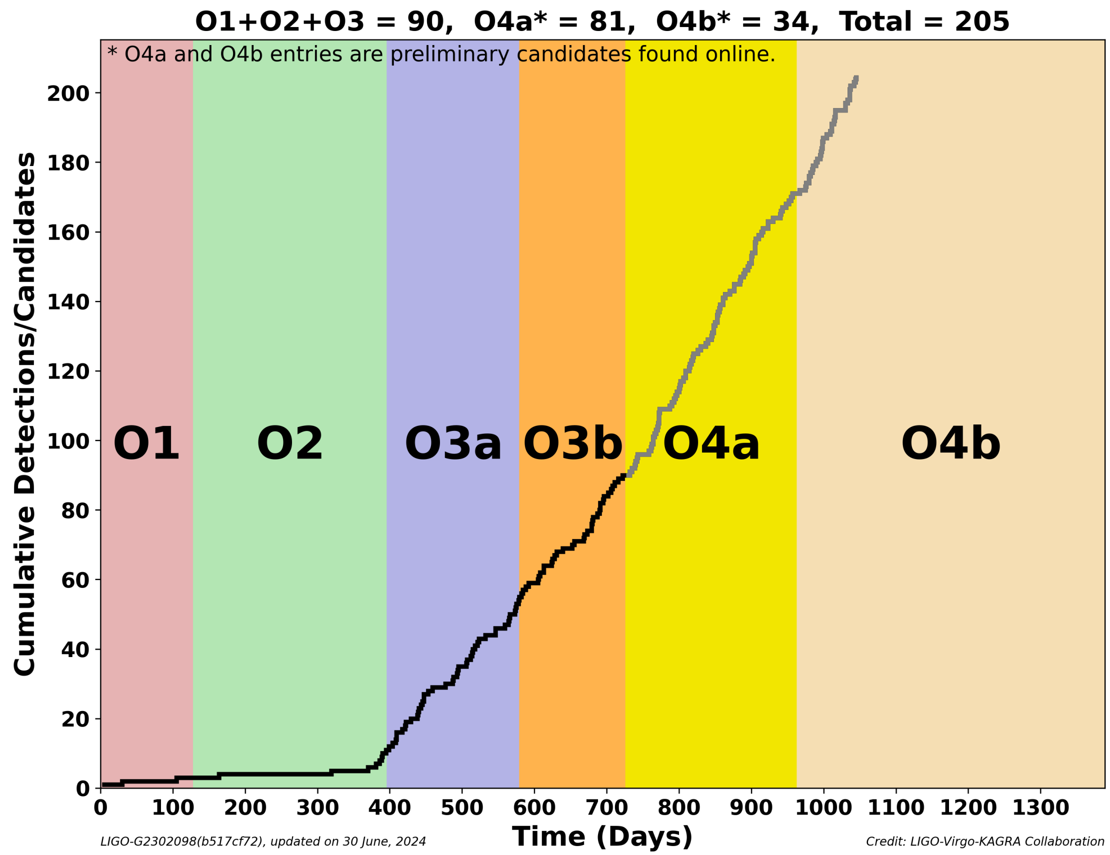
-> Directly model mass distributions of BBH progenitor stars (dashed curve) that undergo stable mass transfer prior to BBH formation

-> prelim results: 10 Msun peak consistent with SMT channel

arXiv:2304.01288

Those were the highlights for O1, O2 O3. What about O4 ?





- The GW horizon is limited by our ability to reduce the noise of the interferometer
- Rate of detected events ~ horizon^3
- O4: May 2023 – June 2025

Beyond binary mergers…

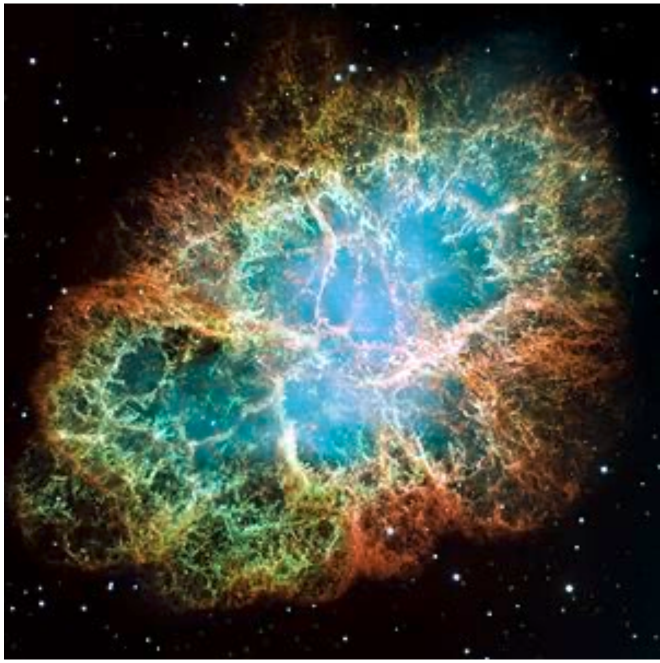
The ever-increasing sensitivity of LIGO will…

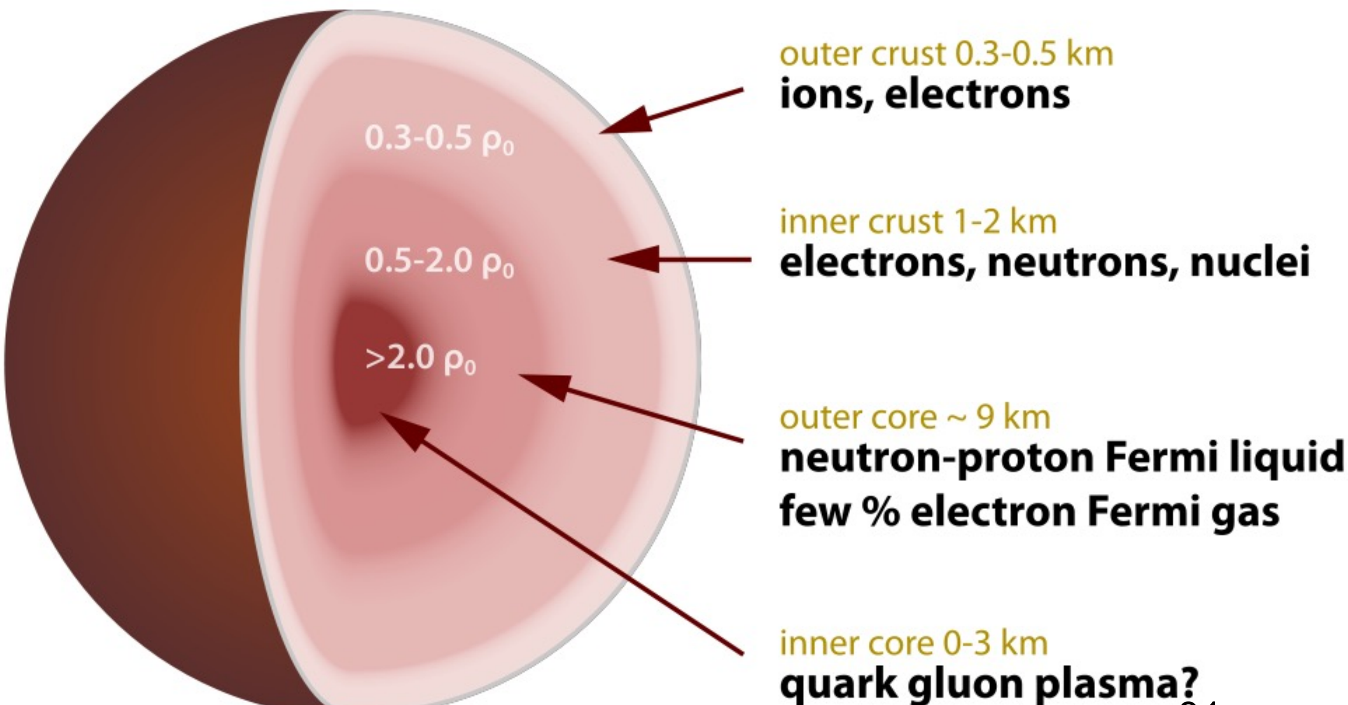
- Allow more observations of mergers of BHs and NSs
  - More
  - Further: In O4 observing BBH mergers to ~6 Gly
    - More short gamma-ray bursts
  - Wider mass range (sub-solar mass?)
  - Greater fidelity (SNR) → details of the GW waveforms

- Allow opportunity for observing new types of GW sources
  - Supernovae
  - Magnetars
  - Long gamma-ray bursts
  - Cosmic strings
  - Cosmic inflation

Neutron stars

- NS result from normal stellar evolution for massive stars in the range 8 to 40 $M_\odot$
  - Fusion to Iron
  - Supernova (Type II)
- Mysterious composition
  - new phases of matter?
- GW observations can tease out the NS composition – equation of state

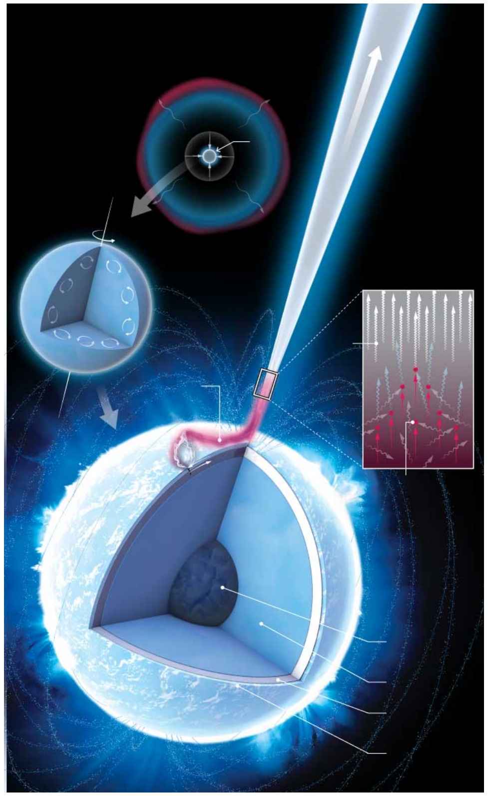


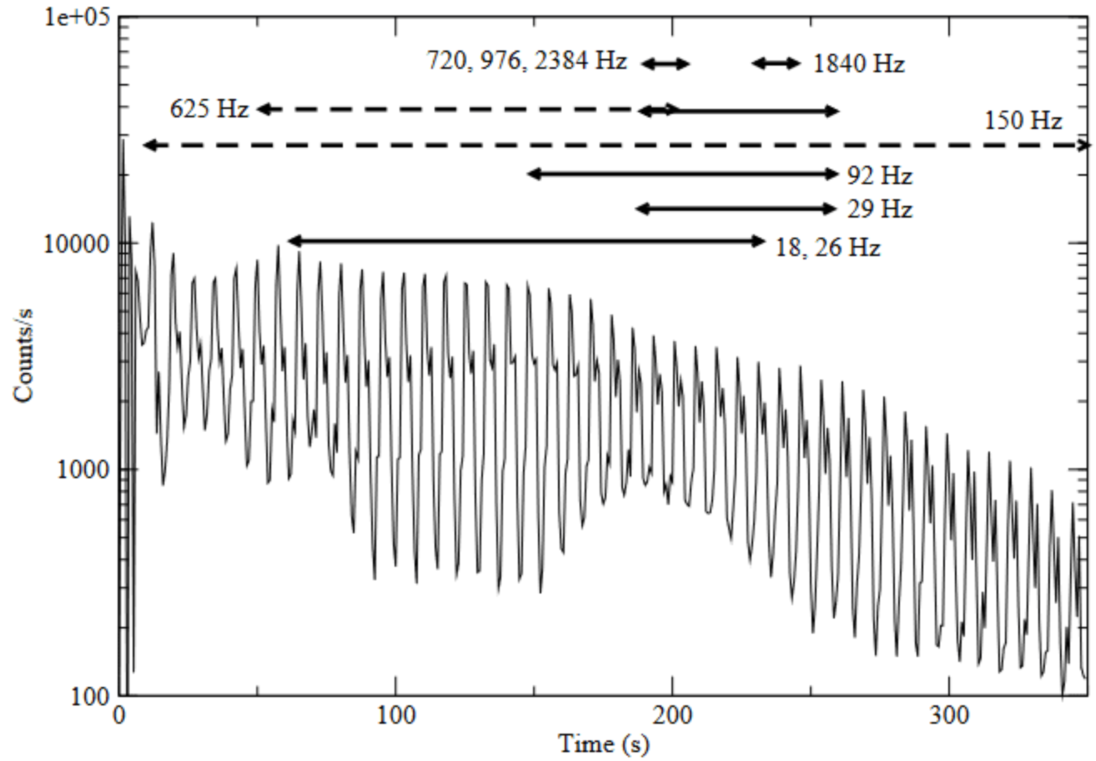


Magnetars

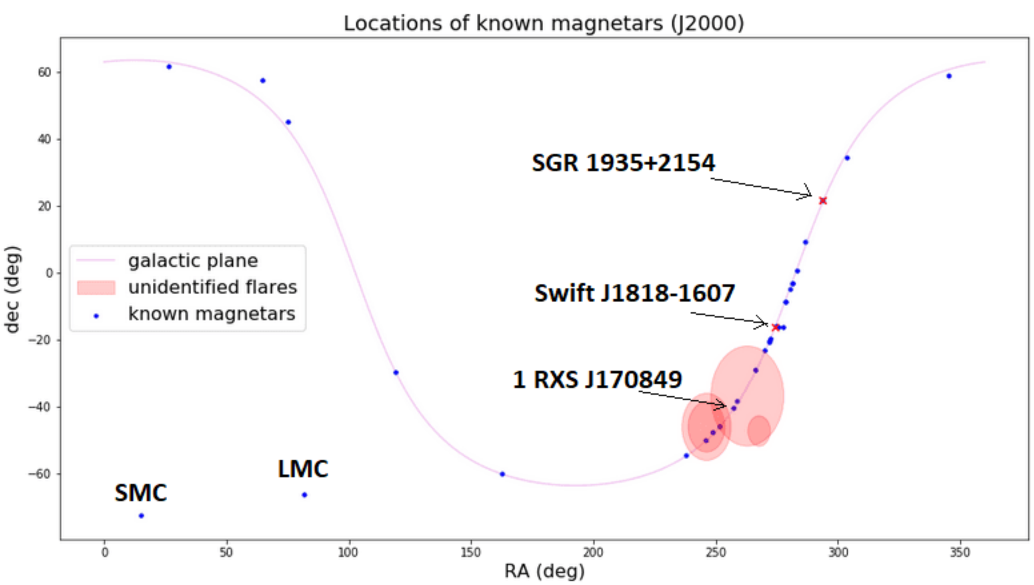
- Magnetars are young neutron stars with magnetic fields about 1000x that of ‘normal’ neutron stars
  - $B \sim 10^{13} - 10^{15}$ G
  - Earth: 0.5 G
- Slowly rotating: few Hz or less (magnetic braking)
- About 90%/10% of core-collapse supernovae result in normal neutron stars/magnetars
- Earth (and satellites!) receive a giant x-ray flare within the Milky Way every 5-10 years
- More frequent smaller x-ray flares

Magnetars and GWs ?





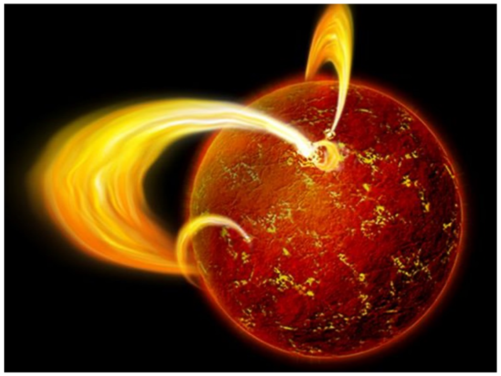
X-rays from 2004 giant flare SGR 1806-20



- Starquakes produce (giant) x-ray flares
- They also ring-up mechanical modes in the magnetar, some (e.g. f-modes) can produce GWs
- ← No giant flares during O3 run, but many ordinary x-ray flares
- UO student Kara Merfeld led the O3 collaboration analysis/paper

Astrophysical inference from NS f-modes

Matthew Ball, Frey, Merfeld
arXiv:2310.15315

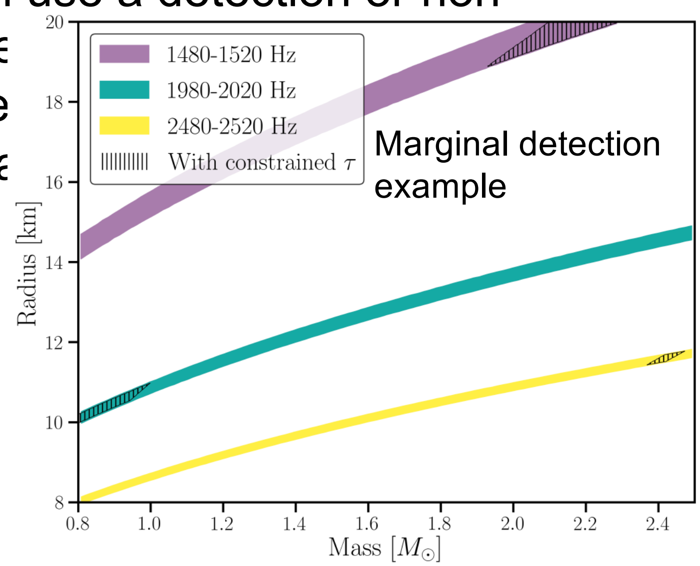


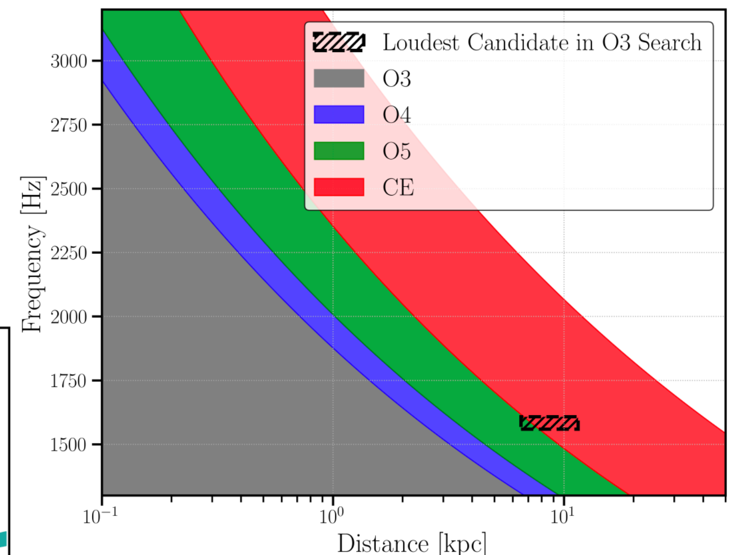
- X-ray flares from magnetars accompany a major perturbation, such as crust cracking or B-field rearrangement
- These probably ring up mechanical modes: f-modes → GWs
- Can use a detection or non-dete
- Use
para

f-modes as damped sinusoids (Andersson & Kokkotas

$$\nu_{GW}(kHz) \approx 0.78 + 1.635\left(\frac{\overline{M}}{\overline{R}^3}\right)^{1/2}$$

$$\frac{1}{\tau_{GW}(s)} \approx \frac{\overline{M}^3}{\overline{R}^4}\left[22.85 - 14.65\left(\frac{\overline{M}}{\overline{R}}\right)\right]$$





Distance/frequency space where 10% of candidates could be detected with SNR>3 for current/future detectors

Vela Glitch of April 29, 2024

Radio observations:

- Rotational frequency changed: $\frac{\Delta f}{f} \sim 2.4{\times}10^{-6}$
- Time of glitch known to ~ +/- 4 s

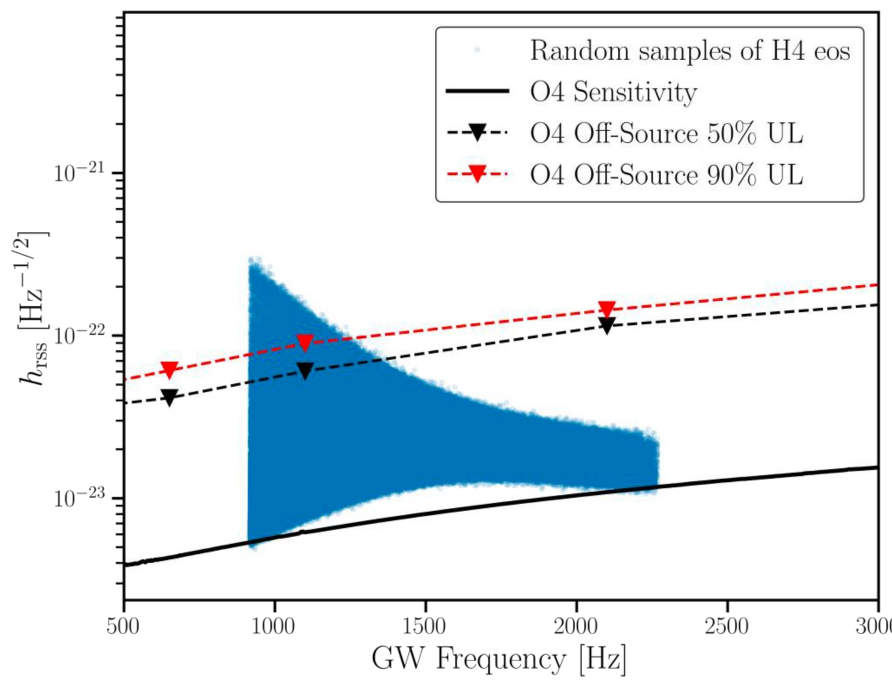
An impulse which can ring up f-modes ?

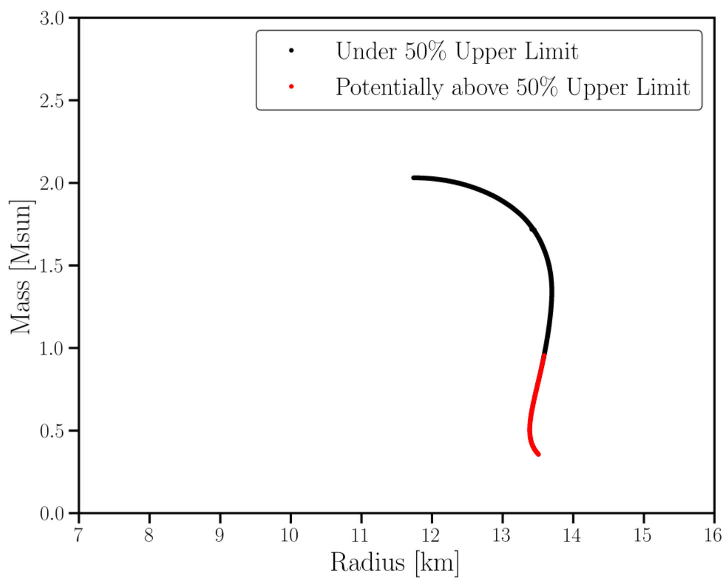
➔ analysis ~ magnetar flare

Vela distance: 267 pc

Matthew Ball, Frey, et al

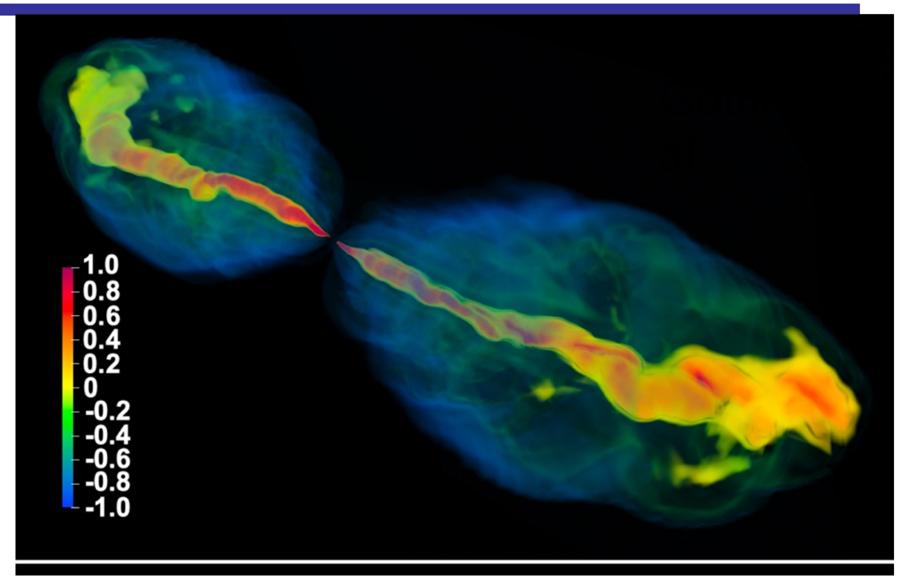
Assume all glitch energy goes into f-modes:

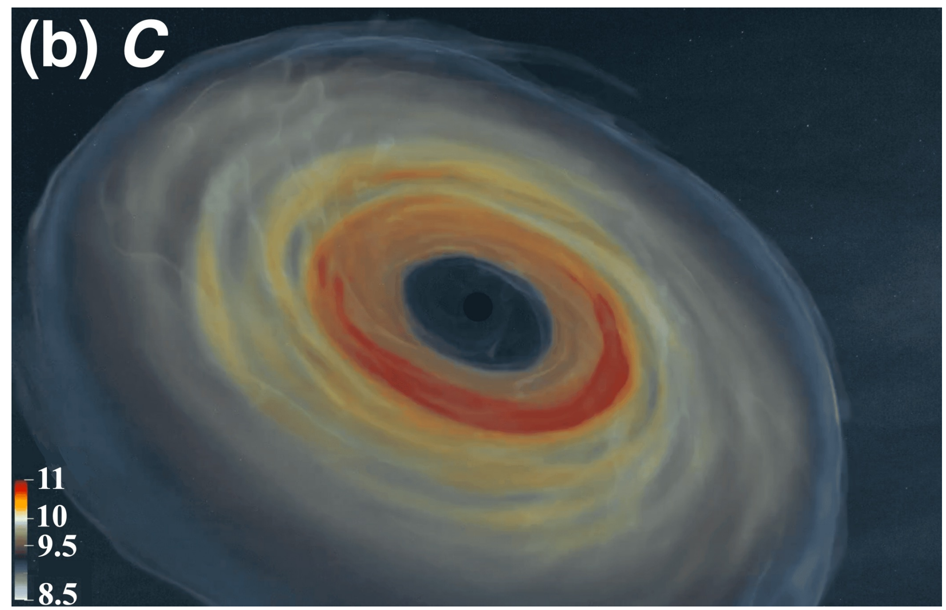




GWs from collapsars

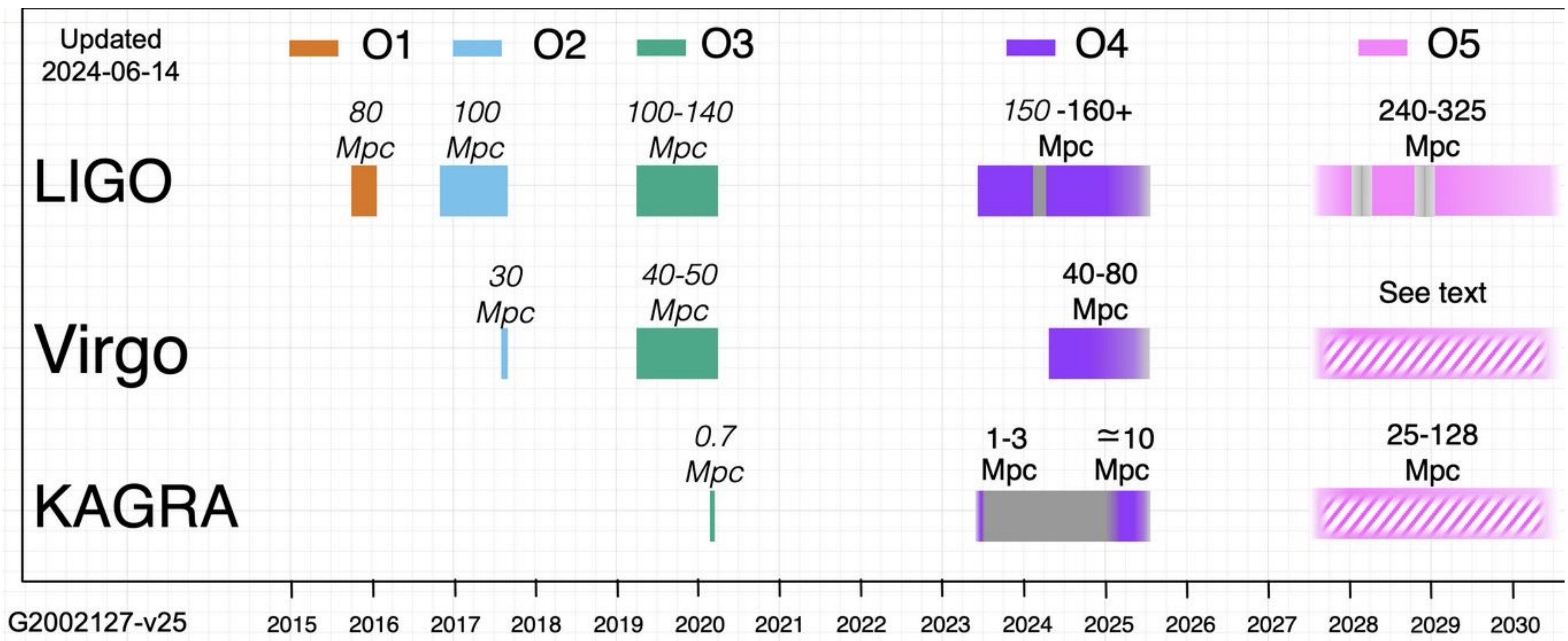
- Collapsars: The collapse of massive, highly rotating evolved stars
- Progenitors of (most) long GRBs (gamma-ray light curves longer than ~2s)
- LGRB placement follows star formation
  - Most distant z~8
  - Nearest 40 Mpc (pre-LIGO)
  - Redshifts largely unmeasured (few %)
- Collapsar accretion disks are potential GW sources – non-homogeneities
- Recent full hydrodynamic simulations optimistic
- GWs from wobbling jets (top)
- GWs from generic accretion disk formation (bottom)



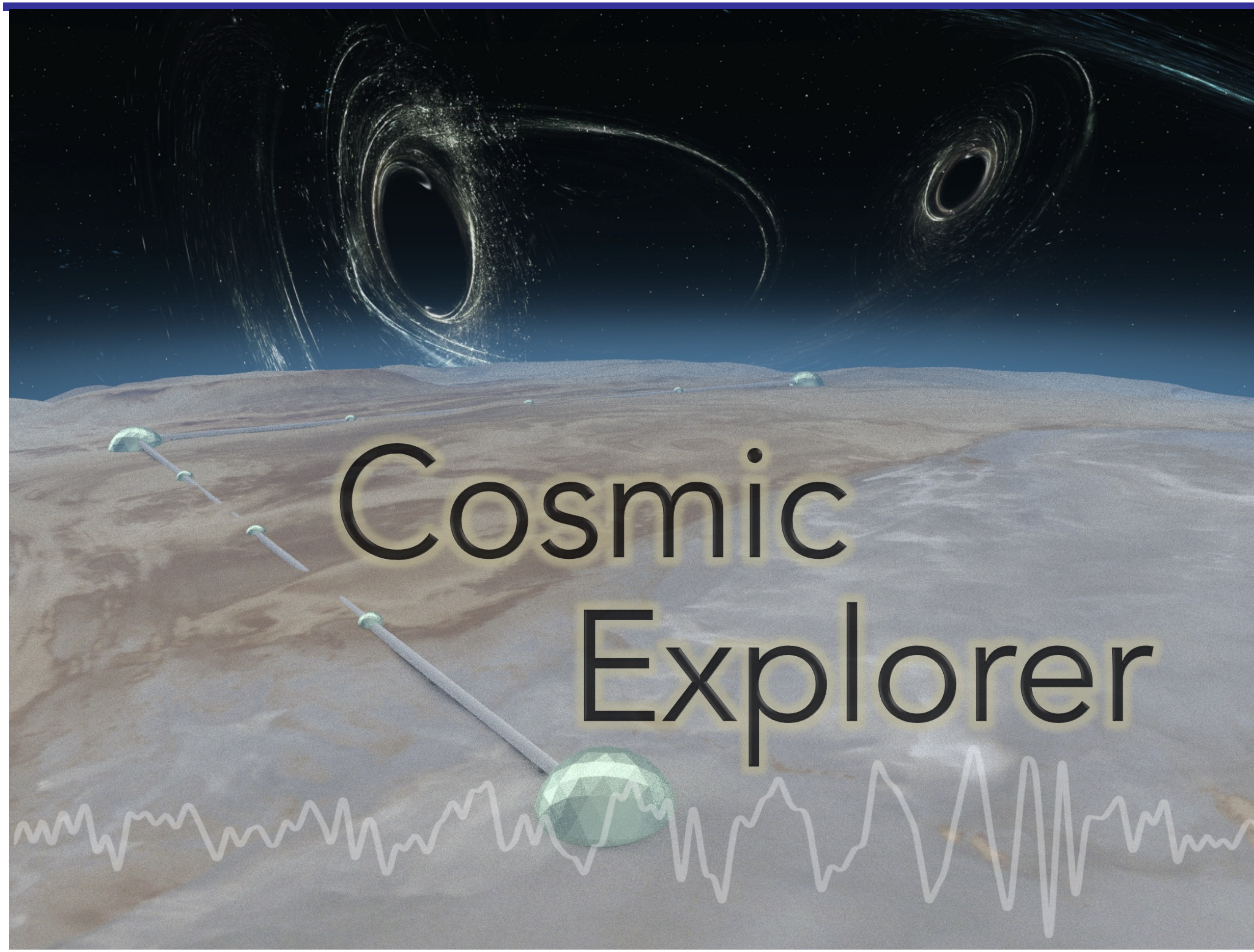


The near future

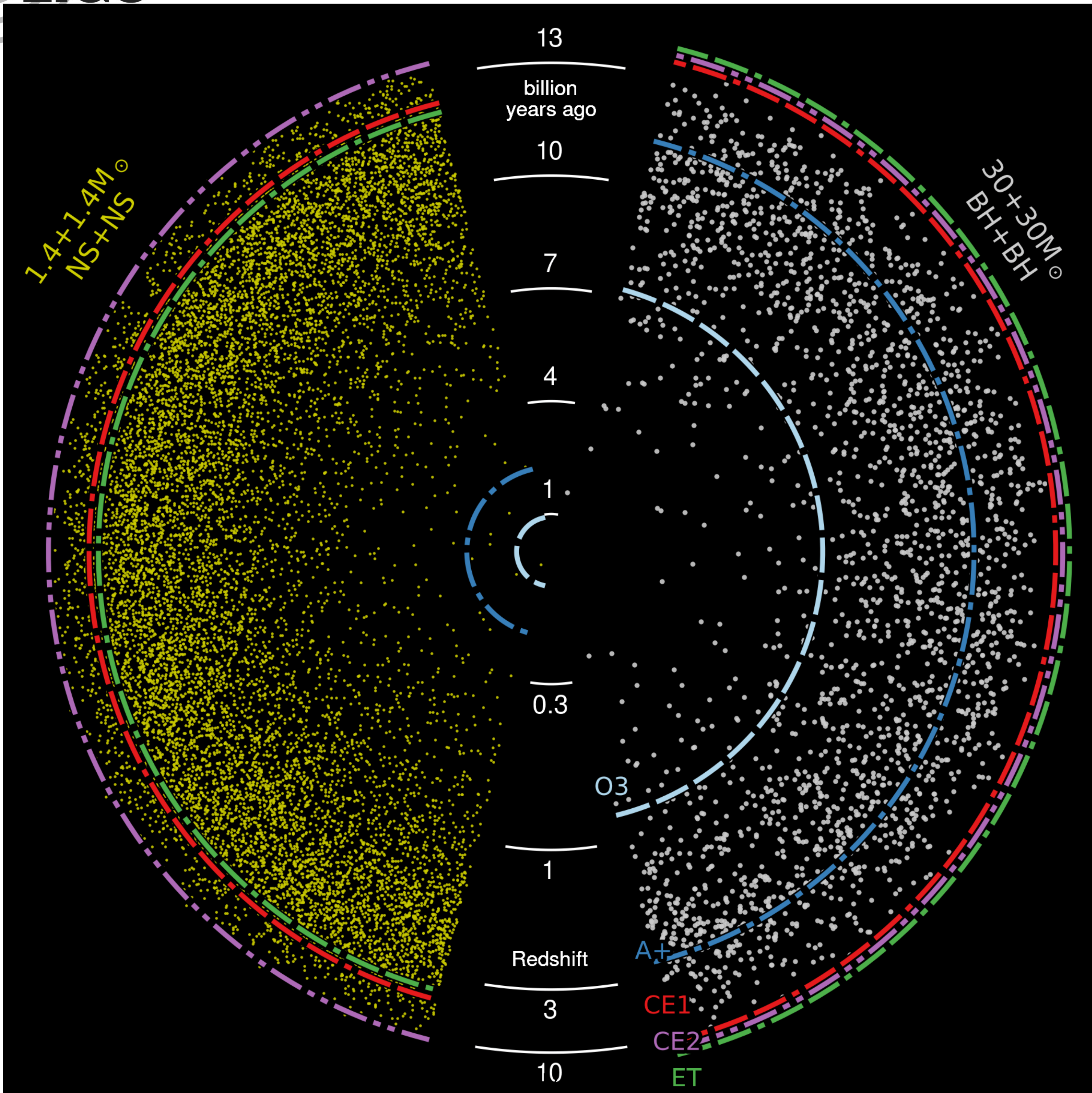
- In O1-O2: about 1 GW event per month
  - GW discovery
  - Binary neutron star merger
- In O3: about 1 GW event per 5-days
  - Routine quantum squeezing
  - 'impossible' high mass black holes
- O4 (started May 24, 2023): more than 2 events per week
  - Frequency-dependent squeezing
  - What new discovery awaits??



The farther future (2030s)



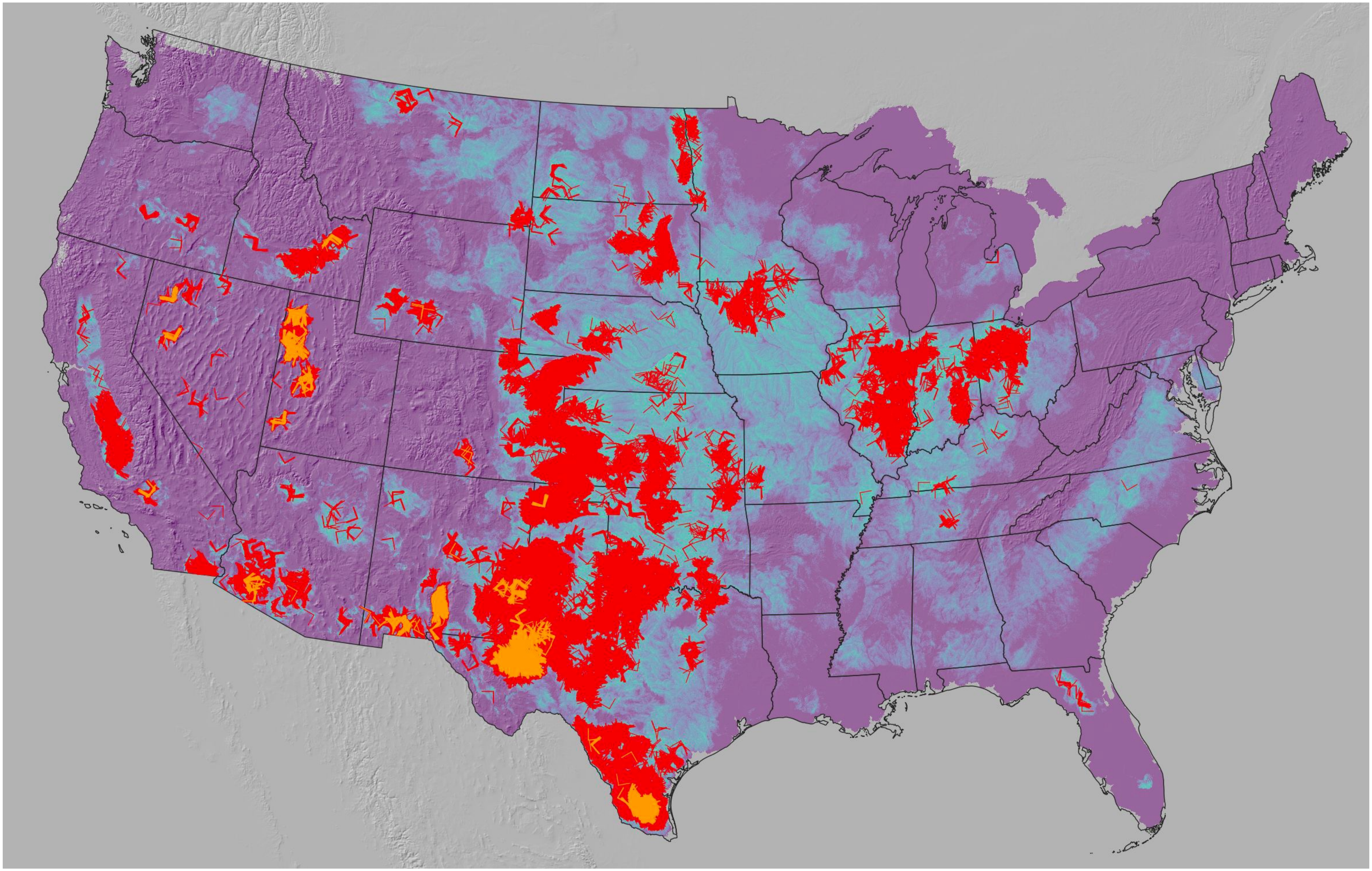
Why CE ?



Also:
10% of BBH will have SNR>1000

1% SNR~10,000

Site Study



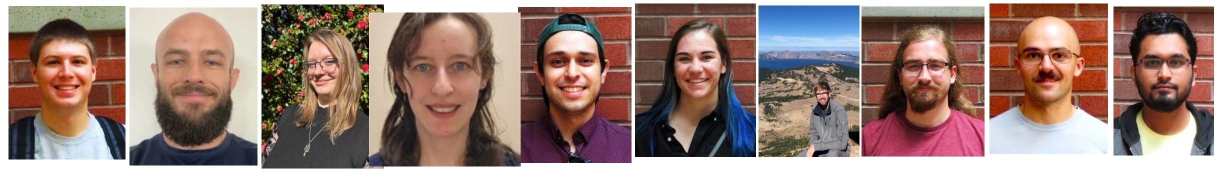
LIGO

Connection to the native people of the site

Yvette Cendes- Radio Astronomer here!

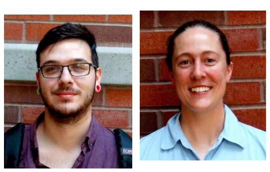
- New faculty member starting this fall!
- Specializing in transient radio astronomy- signals that change over time- using telescopes like the Very Large Array (VLA) in New Mexico
- Research covers a range of astronomical objects, ranging from black holes that shred stars (Tidal Disruption Events, or TDEs), exoplanets, supernovae, gamma-ray bursts…
- Also involved in outreach, in traditional and social media (from editor for the *Guinness Book of World Records* to Reddit)

UO LIGO Group



Graduate Students
Matthew Ball
Lance Blagg*
Samantha Callos*
Gino Carrillo
Genevieve Connolly*
Jaxen Godfrey
Adrian Helmling-Cornell
Benjamin Mannix
JD Merritt
Sangeet Paul

Recent PhDs:
Bruce Edelman
Kara Merfeld



Undergraduate Students
Joshua Iascau
Holden Jose

Faculty
Ben Farr
Ray Frey
Robert Schofield

*LSC Fellows, LHO, Summer, Fall 2024